Managing Coasts with Natural Solutions

Guidelines for Measuring and Valuing the Coastal Protection Services of Mangroves and Coral Reefs

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Contents

List of Figures

List of Tables

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- Sofia Ahlroth, World Bank
- Edward Barbier, Department of Economics and Finance, University of Wyoming
- Dominque Benzaken, The Nature Conservancy
- Brian Blankespoor, World Bank
- Lauretta Burke, World Resource Institute
- Dave Callaghan, School of Civil Engineering, University Queensland
- Gem Castillo, Resources, Environment and Economics Center for Studies
- Bram Edens, Statistics Netherlands
- Lynne Hale, The Nature Conservancy
- Marea Hatziolos, World Bank (retired)
- Lars Hein, Wageningen University
- Cristina Izaguirre, Institute of Hydraulics Cantabria
- Siddarth Narayan, University of California, Santa Barbara
- Barry Nickel, University of California, Santa Cruz, Center for Integrated Spatial Research
- Carl Obst, Melbourne University
- Pascal Peduzzi, Global Change and Vulnerability Unit, United Nations Environment Programme
- Nam Pham Khanh, School of Business, Economics, and Law, University of Gothenburg
- Siyu Qin, Duke University
- Annegien Thyssen, World Bank
- Michael Varden, Australian National University
- Jeff Vincent, Duke University
- Keqi Zhang, Dept. of Earth and Environment, Florida International University

Abbreviations and Acronyms

BSU	Basic Spatial Units
BCR	benefit-cost ratio
CCCCC	Caribbean Community Climate Change Centre
CCP	Coastal Capital Project
CCRIF	Caribbean Catastrophic Risk Insurance Facility
CZM	Coastal Zone Management
EDF	Expected Damage Function
FEMA	Federal Emergency Management Agency
GDP	gross domestic product
IPCC	Intergovernmental Panel on Climate Change
LCEU	Land Cover/Ecosystem Functional Units
MARD	Ministry for Agriculture and Rural Development
MPA	marine protected area
NAP	National Adaptation Plan
NAPA	National Adaptation Program of Action
NatCap	Natural Capital Project
NOAA	National Oceanic and Atmospheric Administration
NWS	National Weather Service
PES	payment for ecological services
PTEC	Policy and Technical Experts Committee
ROMS	Regional Ocean Modeling System
SAP	Strategic Action Programme
SEEA	System of Environmental Economic Accounts
SEEA-CF	System of Environmental Economic Accounting-Central Framework
SEEA-EEA	System of Environmental Economic Accounting-Experimental Ecosystem Accounting
SMS	Surface-water Modeling System
SNA	System of National Accounts
SP	stated preference
TURFS	Territorial Use Rights Fisheries
UNFCCC	United Nations Framework Convention on Climate Change
UNSD	UN Statistical Division
USGS	United States Geological Survey
VARANS	Volume-Averaged Reynolds Averaged Navier-Stokes
WAVES	Wealth Accounting and Valuation of Ecosystem Services
WWF	World Wildlife Fund
WRI	World Resources Institute

Executive Summary

This guidance note provides review and recommendations for how the protective services of mangroves and coral reefs can be measured and valued in a manner consistent with national economic accounts and included in other decision-making processes to support planning for development, disaster risk, and coastal zone management. It synthesizes evidence of the role mangroves (Chapter 2) and coral reefs (Chapter 3) play in coastal protection and risk reduction. It also reviews the tools and approaches commonly used by ecologists, economists and engineers for estimating the coastal protection services of coastal habitats (Chapter 4). Moreover, it examines how the valuations of these coastal protection services can be considered in the System of Environmental Economic Accounts (SEEA), the satellite accounts to the System of National Accounts (SNA) (Chapter 5). In addition, the note examines where the coastal protection role of reefs and mangroves has been used in management decisions from local to national scales (Chapter 6). Finally, it provides recommendations for advancing the assessment and the use of coastal protection values from coral reefs and mangroves in national and regional decisions (Chapter 7).

The executive summary provides a synopsis of the coastal protection role of reefs and mangroves and the recommended approaches for better incorporating these services' role in coastal decision-making processes (for example, coastal zoning, development planning, and disaster risk management) and the SEEA.

In brief, this guidance note finds the following:

- Mangroves and coral reefs provide significant coastal protection benefits.
- For both habitats, the key biophysical characteristics that provide coastal protection benefits can be clearly identified.
- These coastal protection benefits have already been influential in informing conservation, restoration, and management decisions.
- The key coastal protection characteristics of mangroves and reefs can be readily incorporated in to process-based tools used commonly in engineering and insurance sectors.
- In terms of ecosystem service valuation, replacement cost methods are the most widely used for estimating coastal protection services, although production function methods should provide better values for ecosystem accounting.
- This note recommends and details the use of the Expected Damage Function (EDF) approach for estimating and accounting for the coastal protection benefits of mangroves and reefs, with such other approaches as replacement cost to be used when certain conditions are met.

Why Focus on Coastal Protection?

Flooding, erosion, inundation, and extreme weather events affect hundreds of millions of vulnerable people, important infrastructure, tourism, and trade, causing significant human suffering and losses to national economies. In 2011, insured losses from natural disasters reached an all-time high and impacts are predicted to worsen with climate change and population growth. The proportion of the world's gross domestic product (GDP) annually exposed to tropical cyclones has increased from 3.6 percent in the 1970s to 4.3 percent in the first decade of the 2000s (UNISDR 2011). Insurers have paid out more than $300 billion just for coastal damages from storms in the past 10 years, which often goes toward rebuilding similar coastal infrastructure that is still vulnerable to coastal storms and flooding.

Coastal and marine habitats, particularly coral reefs and mangroves, can substantially reduce exposure and vulnerability, providing natural protection from risk. Yet the value of these systems as "green infrastructure" is still not fully recognized, and they continue to be lost and degraded. The Global Assessment Report on Disaster Risk Reduction highlights that economic loss risk resulting from tropical cyclones and floods is growing as exposure of economic assets increases and the status of ecosystem services degrades (UNISDR 2011), and that societies are excessively discounting risk in development choices, particularly in coastal areas (UNISDR 2015). In terms of habitat loss statistics, 30 to 50 percent of wetlands have already been lost (Zedler and Kercher 2005), 19 percent of mangroves were lost from 1980–2005 (Spalding et al. 2010), and 75 percent of the world's coral reefs are now rated as threatened (Burke et al. 2011).

The trends in habitat loss and the concomitant loss of coastal protection services will continue unless the values of these habitats are accounted for in policy and management decisions. The importance of mainstreaming the coastal protection value of mangroves and reefs is great, as there are substantial opportunities and risks that will affect the ecosystems and the communities that rely on their services during the next 5 to 10 years. Sixty percent of the world population is expected to live in urban areas by 2030, with a greater concentration in coastal areas. As coastal development increases, there will be heavy investments in coastal infrastructure and the potential loss of more coastal habitats and their services.

Billions of dollars are being dedicated to reduce risks from disasters and climate change, creating both threats and opportunities for natural systems. Total Fast Start Finance commitments under the United Nations Framework Convention on Climate Change (UNFCCC) through 2012 include roughly $3 billion for climate adaptation assistance. In the United States, the Federal Emergency Management Agency (FEMA) spends $500 million per year to reduce flooding hazards. Middle-income countries—such as Brazil, China, and Colombia—are making multibillion dollar investments to address the risks of flooding and other disasters exacerbated by climate change. Most of these funds are destined for the creation and maintenance of "grey infrastructure," such as seawalls, which will further degrade coastal ecosystems, and may not be cost effective for risk reduction when compared to more natural and hybrid alternatives.

Following the 2004 Indian Ocean tsunami and Hurricane Katrina in 2005, there has been substantial scientific focus on recognizing and quantifying the benefits from mangroves and coral reefs. There has also been an increasing focus on identifying the policies needed to encourage ecosystem protection and restoration specifically for hazard mitigation and risk reduction.

The World Bank WAVES Program

Wealth Accounting and Valuation of Ecosystem Services (WAVES) is a global partnership led by the World Bank that aims to promote sustainable development by mainstreaming natural capital in development planning and national economic accounting systems (SNA), based on SEEA. This global partnership (www.WAVESpartnership.org) brings together a broad coalition of governments, UN agencies, nongovernmental organizations, and academics for this purpose.

Eight developing countries—Botswana, Colombia, Costa Rica, Guatemala, Indonesia, Madagascar, the Philippines, and Rwanda—are currently partnering with WAVES to establish natural capital accounts. More are expected to join during the next two years. These accounts include experimental accounts for ecosystems and ecosystem services, and mangroves have been identified as a priority ecosystem for some countries. The methodology for measuring and valuing the provisioning and tourism services of mangroves and reefs is well established and these values are, in principle, included in the national economic accounts. But methodology for including these regulating services in national economic accounts—notably, coastal protection services, fisheries enhancement, and carbon storage—is still in an experimental stage and there is not yet international agreement on their measurement. Guidance is needed for countries that want to build comprehensive accounts for mangroves and reefs that include all these services.

The WAVES Policy and Technical Experts Committee (PTEC), which was established in the fall of 2012, has a mandate to guide the development and implementation of scientifically credible methodologies for ecosystem accounting, identify opportunities to contribute to policy and mainstreaming, and ensure cohesion, consistency, and scalability among the country studies. This guidance note has been developed under PTEC.

The Coastal Protection Role of Coral Reefs and Mangroves

There is a large and growing body of scientific evidence on coral reef and mangrove coastal protection services and many on-the-ground projects that demonstrates the value of these ecosystems for coastal protection. Coral reefs and mangroves can substantially reduce vulnerability and risk by providing natural protection from flooding and erosion, which is important to hundreds of millions of people globally. Field measures, models, and demonstration projects provide strong evidence of the coastal protection benefits of mangroves and reefs. Coral reefs and mangrove forests should no longer be considered to be a novel way to defend the coast.

Mangroves

Mangroves provide a variety of ecosystem services to adjacent coastal populations, such as the provision of food and timber products, and they provide coastal defense services by reducing risk from coastal hazards. Studies (summarized in Figure 2.1) have found that mangroves significantly attenuate waves. Studies suggest wave height can be reduced by 13 to 66 percent over a 100-meter-wide mangrove belt, while wave height can be reduced by 50 to 100 percent over a 500-meter-wide mangrove belt.

Wave height reduction within a mangrove forest depends on the width of the forest, mangrove tree morphology, water depth, topography, and wave height. Mangrove species with aerial roots are more effective at attenuating waves in shallow water, when the waves encounter the roots. Species without aerial roots are better able to attenuate waves when the water level reaches the branches. The mangrove vegetation reduces wind speeds over the water surface, lessening the likelihood of waves increasing in height within mangrove areas. Mangroves affect local topography over longer-term scales through their effect on sedimentation, erosion, and the maintenance of tidal creeks and channels. In demonstration projects, this erosion reduction and sedimentation can lead to the buildup of land and shifts toward less intertidal species in the coastal community.

Evidence for the ability of mangroves to reduce storm surge flood depths and associated damage comes from three sources: direct observations of water level heights; the use of well-validated numerical models that simulate storm surge behavior in the presence or absence of mangroves; and observations of the damage caused and the number of lives lost from storm surges in areas with mangrove loss (see Table 2.2). Both empirical data and numerical models suggest that mangroves can play a role in reducing storm surge peak water levels when the mangroves are present over sufficiently large areas. Studies measured reductions in peak water levels of 4 to 48 centimeters per kilometer of mangrove. In low lying areas, even relatively small reductions in peak water levels could reduce flood extent and, hence, damage to property.

The relationship between storm surge reduction, bathymetry, topography, distance from shore, and width of mangrove vegetation is highly complex (like most coastal processes), but it is increasingly well understood. Topography is the most important local factor affecting inundation from storm surges, interacting with the peak water level to influence the extent of inundation. The ability of mangroves to reduce storm surges depends on the storm surge forward speed, the height of the storm surge, and the cyclone intensity. Numerical models suggest that mangroves will be more efficient at reducing surge height for fast-moving surges. Extreme events, with very strong winds or surges many meters high, may damage or destroy mangroves, reducing their ability to reduce surge height.

Studies suggest that mangroves can also reduce tsunami flood depth, current velocity, tsunami pressure, hydraulic force, run-up height/distance, and inundation extent. Flood depth is expected to be reduced by 5 to 30 percent by mangrove belts that are several hundred meters wide. In addition to mangrove width, other key factors influencing the rate of reduction of tsunami characteristics include vegetation density, whether the tsunami is a breaking or nonbreaking wave, and wave period. Tsunamis above approximately 4 meters in height are likely to destroy mangroves, rendering them ineffective at reducing tsunamis.

Coral Reefs

Coral reefs naturally protect coasts from erosion and flooding by attenuating wave energy and supplying and trapping sediment found on adjacent beaches. Recent meta-analyses by Ferrario et al. (2014) show that coral reefs reduce wave energy by up to 97 percent. Reefs function much like low-crested breakwaters for wave attenuation and their behavior is well characterized in models and field demonstrations (Sheppard et al. 2005; Gallop et al. 2014). They protect shorelines primarily by dissipating wave energy, mainly by breaking waves at the seaward edge and through bottom friction as the waves move across the reefs (Hardy and Young 1996; Wolanski 1994). Factors determining coral reef wave attenuation include the following: depth of water above the reef surface; its cross-shore bathymetric profile; and reef rugosity or surface roughness.

Healthy reefs can provide coastal protection, even during cyclones with strong wave conditions (Blanchon et al. 2010). Coral reefs also generate massive amounts of carbonate as they grow and are generally expected to be able to keep pace with sea level, if they are healthy. Thus coral reefs could require little direct maintenance costs for coastal protection, if they remain healthy. However, declines in the condition of coral reefs in places (for example, Great Barrier Reef, see De'ath et al. 2012; or the Caribbean, see Jackson et al. 2014) coupled with increasing rates of global sea-level rise are jeopardizing communities and coastal infrastructure, particularly in low-lying small island developing states. Furthermore, the potential impacts of climate change, including sea-level rise and coral mortality under warmer and more acid waters (IPCC 2014), may reduce the protection the coral reefs offer at present (Baldock et al. 2014; Hoegh-Guldberg et al. 2011).

Reducing threats to coral reefs, such as overfishing and poor water quality, along with establishing marine reserves, can all directly benefit reefs and maintain their shoreline protection services. Degraded reefs can be structurally and functionally restored using both biological and physical techniques, including the use of artificial reefs. Reef restoration has been shown to be cost effective in comparison to the development of submerged breakwaters (CCRIF 2010; Fabian et al. 2014; Ferrario et al. 2014). Incorporating nature-based principles into engineered designs can also yield ecological benefits (Waterman 2008). Merging both ecological and engineering schools of thought into more mixed integrated designs can yield multiple benefits and will ultimately be more cost effective than traditional hard infrastructure solutions.

Recommended Approaches for Estimating Coastal Protection Benefits from Mangroves and Reefs

The methods for estimating the role and value of natural habitats in coastal protection and risk reduction include index-based and process-resolving approaches. This guidance note reviews both (i) the common coastal ecosystem service tools and (ii) the engineering tools, models, and approaches for estimating coastal risks and the role of habitat (and other infrastructure) in reducing erosion and flooding to avert economic and social damages.

Index-based approaches use estimates of exposure and vulnerability to assess risk and risk reduction benefits. These indices can be (re)calculated using different configurations of natural habitats or other environmental conditions (such as sea level) to estimate potential changes in risk or benefits. For example, the Coastal Vulnerability Module of InVEST (Arkema et al. 2013) uses an index-based approach to assess shorelines most at risk to flooding with and without coastal habitats. The index scores seven variables (for example, winds, wave surge, sea level, and habitat type) on a scale of one to five to indicate exposure of the shoreline.

Process-resolving approaches, on the other hand, define meteo-oceanographic variables, such as waves, storm surges, currents, tides, and sea level, and examine coastal processes, such as sediment transport and interactions between waves and structures, to assess risks and the value of habitats in reducing exposure. Process-resolving approaches can be further delineated into analytical approximations and numerical models. **Analytical approximations** of coastal processes or semi-empirical formulations (for example, propagation of waves over vegetation fields, such as Mendez and Losada 2004) have low computing capacity requirements and are affordable to implement at large scales. **Numerical models** resolve coastal processes with higher accuracy, but can require significant computing capacity and expertise.

More complex and accurate tools require more technical expertise and computing capacity, which can limit the geographic scale at which process-resolving tools are used. Thus, the geographic scope of the analysis often defines which approach is used to estimate coastal risks and protection benefits. Global or national-scale analyses often use index-based approaches that combine hydrodynamic (for example, mean wave height), geophysical (for example, geological features), and socioeconomic (for example, population density) data into a unique metric or index (for example, the United States Geological Survey [USGS] Coastal Vulnerability Index). Local-, regional-, and global-scale studies are often able to employ process-resolving approaches that numerically model factors, such as wave propagation, onshore flooding, or sediment movement. Although process-resolving approaches require more technical expertise, they can be included in large-scale assessments of coastal protection values, benefits, and services by using semi-empirical models or analytical equations for ideal conditions.

This guidance note recommends using process-based approaches in general and further recommends an Expected Damage Function (EDF) approach for valuing the coastal protection services from reefs and mangroves. The EDF is adapted from approaches commonly used in engineering and insurance to assess risks and benefits. **There are five core steps to estimating coastal protection benefits from any kind of infrastructure:**

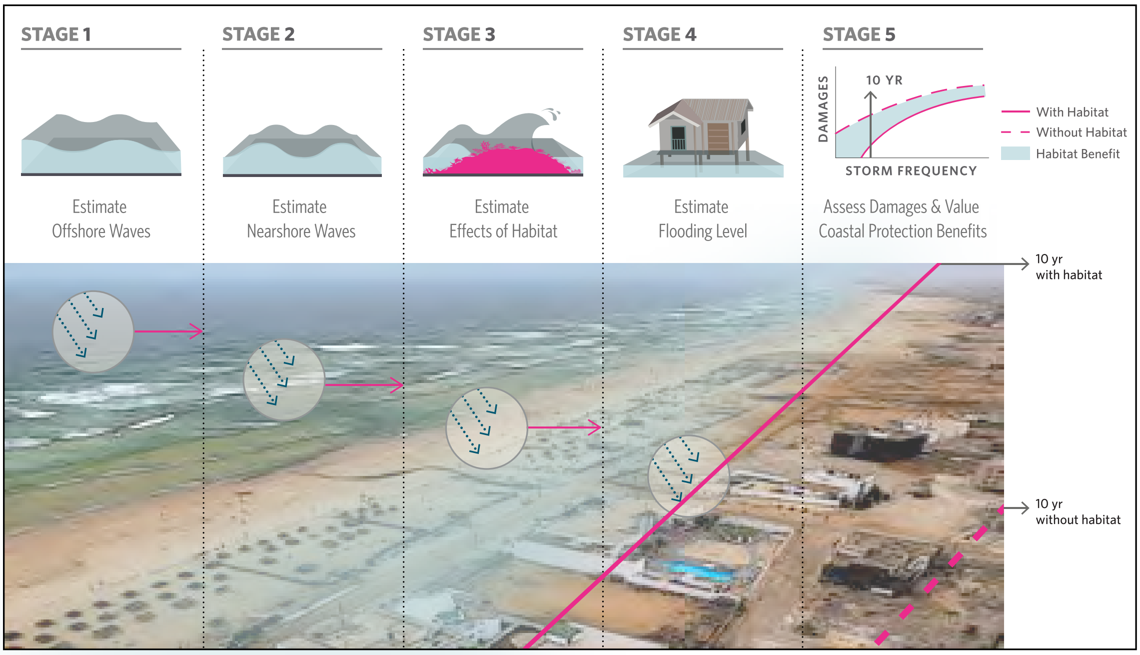
1. Estimate offshore hydrodynamics
2. Estimate nearshore hydrodynamics

3. Estimate effects of coastal structures (habitat) on hydrodynamics
4. Estimate flooding or erosion
5. Assess expected and averted damages (value coastal protection benefits).

Together, these five steps allow an assessment of coastal habitat protection benefits in terms of damages averted by conserving or restoring the habitats (Figure ES1). Each of these five steps represents a different type of problem to be solved, and there is a suite of tools and models for solving each (see Table 4.1 and Appendix 4.2). The engineering and insurance sectors commonly use these steps to estimate coastal risks and assess infrastructure alternatives for risk reduction and climate adaptation (for example, CCRIF 2010; Economics of Climate Adaptation 2009). The note describes these steps in general terms below. Most of the steps are similar for reefs and mangroves, with the exception of the third step. These steps describe and advance an EDF approach to assessing benefits from habitats (for example, Barbier 2007).

1. *Estimate Offshore Hydrodynamics.* The study of coastal protection starts with the oceanographic conditions that generate waves from wind in deep waters. Wave generation is well understood, and models and numerical databases are available to estimate these terms (for example, WaveWatch 3). Coastal applications also require an assessment of winds, waves, mean sea level, tides, and storm surge. A key result of this step is an assessment of both average and extreme offshore conditions in the region.
2. *Estimate Nearshore Hydrodynamics.* Waves change significantly throughout their propagation from deep to shallow waters because of interactions with the bathymetry and coastal morphology (although other factors, such as wind transfer, can also affect the waves). In their propagation in nearshore environments, waves experience refraction, dissipation, diffraction, and other sources of energy transfer. A key result from this step is a characterization of nearshore wave heights and energy. These wave heights and energy are typically assessed across a range of average and extreme conditions (for example, see Economics of Climate Adaptation 2009: USACE 2002).
3. *Estimate the Effects of Coastal Structures (Habitat) on Hydrodynamics.* Nearshore waves then interact with habitats (or other structures), which results in wave attenuation and wave energy reduction. The models for estimating the effects of offshore structures (such as reefs) and intertidal vegetation (such as mangroves) are different. For instance, coral reefs attenuate short waves (for example, wind waves) mainly through wave breaking and wave energy dissipation, depending on relative depth, rugosity, and reef geometry. In contrast, mangrove forests can attenuate both short-wave energy and long waves (for example, storm surges).
4. *Estimate Onshore Flooding or Erosion.* After passing over habitats, the remaining wave energy is translated into levels of onshore flooding or erosion. The models and equations for assessing erosion and flooding are different. At present, most considerations of expected and averted damages focus on flooding impacts and rarely assess erosion. For flooding, a key result of this step is an assessment of onshore flooding levels relative to storm frequency (return periods). As a first-order estimate, a bathtub approach is usually taken where the flood height (water level) at the shore is distributed across land based on topographic elevation creating a flooding envelope. More complex flooding models take into account different land uses (such as different rugosity) and coastal defenses (such as barriers and protections).
5. *Assess Expected and Averted Damages (Value Coastal Protection Benefits).* After flooding levels are modeled as a function of event frequency (for example, flood height versus storm return period), the next step is to assess the damages or losses from the events. The main

Figure ES1: Conceptual Diagram of the Process-based Steps for the Assessment of Flooding and the Role of Habitats in Flood Reduction



analysis is a calculation of the people and assets within ("under") the flooding envelope (see Figure ES1). The expected damages can be adjusted by elevation with a vulnerability curve that characterizes past observed relationships between flood height and damage to structures. For example, a structure flooded by 0.3 meters of water will have less percent damage than a structure flooded by 3 meters of water.

Spatially explicit data on the distribution of people and assets are necessary to calculate potential damages. In the absence of detailed spatially explicit information, the most common approach for assessing the distribution of coastal assets for large-scale studies is to spatially allocate a country's GDP or subnational GDP based on population estimates, that to translate exposed populations into exposed assets using an estimate of produced capital per capita (see World Bank 2010; Hallegatte et al. 2011, 2015). A dataset of global gridded GDP using this approach is currently available from UNEP-Grid and the World Bank.[1]

A key result of the analyses in this step is the development of an expected damage function that describes the likely value of assets flooded under different storm frequencies or return periods (for example, once in 10-, 100- and 500-year storms). The final analysis in the assessment is the comparison of the differences in expected damages with and without coastal habitats. This difference represents the value of the coastal protection benefits.

There are several possible outputs from this five-step approach. The first product is an assessment of existing risk, which is usually expressed as the *Expected Damage Function*. The second product is a comparison of expected damages with and without coastal habitats (see Fig ES1). The difference in these functions is an estimate of the coastal protection benefits of reef

1 http://preview.grid.unep.ch/index.php?preview=data&events=socec&evcat=1

and mangrove habitats. These comparative results are sometimes referred to as *averted damages.* The value of these benefits can be calculated either (i) by comparing the difference in expected and averted damages at one or more specific storm return periods and/or (ii) by integrating the area between the curves (Figure 4.2), which represents the average annual averted damages, that is, annual expected benefit from the habitats (Olsen et al. 2015) This value is most consistent with other values in the annual accounts.

Existing Valuation Studies and Approaches for Integrating Ecosystem Service Values into National Accounts

A large suite of tools and approaches for ecosystem service valuation is available. Each method is suited for specific ecosystem services and requires different types of data and data collection methods, from personal surveys to property prices and attributes and beyond. A body of literature exists on the valuation of ecosystem services generated by mangroves and coral reefs, but it is limited in the number of studies and their geographic coverage. Most valuation studies come from Southeast Asia. The EDF approach assumes that the value of an ecosystem (mangrove or coral reef) can be estimated by the reduction in damage expected from storms and flooding. It provides conceptually valid estimates of economic value and is also aligned with concepts of value in the System of National Accounts. This approach has been widely used in the engineering and insurance industry, but has not been as widely implemented in economic valuation.

In a survey of the literature, the replacement cost was found to be the most commonly used valuation method for coastal protection services. It is based on the cost of providing built infrastructure, such as seawalls, to replace the protective services of mangroves and coral reefs, particularly flood protection and storm surge protection. This method has been used largely because there is extensive experience in building hard infrastructure to provide coastal protection, and it is relatively easy to obtain figures for the cost of a seawall of a particular length, replacing a mangrove forest. However, economic theory cautions that the replacement cost approach provides a valid measure of economic value only under highly restrictive conditions that are often not met, or even tested for in the studies that used this approach. These criteria require that (i) the same service is supplied by the ecosystem and the alternative provider, (ii) the replacement alternative is the least cost replacement option, and (iii) the replacement alternative would actually be implemented, if unavailable from the ecosystem.

There have been considerable data challenges to implementing the EDF approach in the past. The development and greater use of biophysical models to assess the role of mangroves and coral reefs in preventing flooding and erosion and to estimate expected damage prevention can provide a more systematic and consistent method to assess benefits from protective services.

Natural Coastal Protection in Policy and Practice

The coastal protection benefits of mangroves and reefs have informed both policy and practice. There are clear examples over the last several decades where these benefits have led to significant habitat conservation and restoration actions as well as changes in coastal policies. This note reviews more than 20 case studies (see Table 6.1) where the coastal protection role of mangroves and reefs was reflected in five major types of decisions: (i) planning and land use decisions, including coastal zone management; (ii) coastal defense infrastructure projects; (iii) national risk and adaptation planning; (iv) habitat restoration; and (v) post disaster recovery. The guidance note identifies lessons learned and opportunities to advance the use of mangroves and coral reefs for coastal protection from the review of existing policies and projects.

Most importantly, there have been a number of key triggers behind policy change and decisions supporting natural coastal protection:

i. Community-based demand for coastal protection, particularly from mangroves, which is often motivated by observed losses of habitat and the ensuing impacts
ii. Clear scientific evidence in ecology, economics, and engineering of protection benefits and cost effectiveness of nature-based defenses
iii. International obligations and funding, particularly for green climate adaptation;
iv. Post-disaster rebuilding and restoration that incorporates ecosystems
v. Demand for other benefits, such as food security and jobs with natural coastal protection as an ancillary benefit.

Recommendations

Based on the review and analysis, this note identifies recommendations for advancing the assessment and incorporation of coastal protection values from coral reefs and mangroves in policy decisions (Chapter 7). This executive summary identifies the top 10 of these specific recommendations.

- **Coral reefs and mangrove forests should no longer be considered a novel way to defend the coast.** As offshore breakwaters, the basic engineering models of how reefs provide coastal protection are well known. Engineering models and field demonstrations of the role of mangroves in flood and erosion reduction have been developed over the past several decades and clearly demonstrate effectiveness.
- **The most important data gap in more accurately estimating reef coastal protection services is nearshore bathymetry,** particularly near the reef crest. This is a critical gap for understanding coastal processes along many tropical coastlines. Greater emphasis should be focused on collecting this data using a variety of approaches, including depth sounding, side-scan sonar, and imagery inference (such as SeaWifs). **The most important gaps in estimating mangrove coastal protection services are forest density and structure,** which are used to estimate friction values in engineering models and data to validate surge models**.**
- **The EDF approach is recommended for valuing coastal protection benefits**. Caution should be applied when using replacement cost valuation to ensure it meets the necessary conditions, since the approach tends to overestimate values of coastal protection. But this approach is recognized as a second best alternative and often easily implemented approach, if it is not possible to do an EDF approach.
- **Pilot projects are needed that incorporate coastal protection services into natural capital accounting.** These projects should follow the approach in the UN Statistical Division (UNSD 2013) System of Environmental-Economic Accounting/Experimental Ecosystem Accounting (SEEA/EEA). Pilot projects should consider a number of issues, such as developing estimates of future service flows and their valuation over time. However, this publication notes that such issues as **Basic Spatial Units (BSU) and Land Cover/Ecosystem Functional Units (LCEU) may be very straightforward to develop for protective services of reefs and mangroves (see Chapter 5).**
- **Many countries need to develop national coastal risk maps. This is a critical first step for overall risk reduction and coastal protection.** Many countries are moving toward developing these maps, creating opportunities to include natural protection benefits in planning. **These national risk maps should identify where and how much risk reduction value is currently**

provided by reefs and mangroves (that is, identify variation in coastal protection benefits nationally). These maps would then also prioritize where coastal habitat protection and restoration offer the greatest risk reduction.

- **In many places some of the most cost-effective solutions for coastal protection will be to reduce threats and improve management of existing mangroves and coral reefs.**
- **Where these ecosystem services have been lost, the restoration of reefs and mangroves should be considered as one of the key alternatives evaluated for returning these coastal protection benefits.** Restoration has been shown to be cost effective for coastal protection in comparison to other approaches, such as submerged breakwaters. However, restoration should not be used to create novel habitats (that is, putting mangrove or reef-like structures in areas where they did not previously exist).
- **Develop guidelines or best practices for restoration of mangroves and reefs for coastal protection.** There is a growing body of guidance on mangrove restoration, which, while very good, can still be enhanced. There is little-to-no guidance on best practices for reef restoration for coastal protection.
- **Develop large scale commitments to conserve and to restore degraded mangroves and coral reefs.** In Vietnam, the amount (hectares) of mangrove conservation and restoration has been at the same scale as the past loss of these habitats. Few other countries have made such commitments.
- **More developing nations should include reefs and mangroves in their national adaptation plans and more developed nations should incorporate coral reef and mangroves in to their support programs for adaptation and risk reduction (such as in green adaptation funds).**

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1| Introduction

Flooding, erosion, inundation, and extreme weather events affect hundreds of millions of vulnerable people, important infrastructure, tourism, and trade, causing significant human suffering and losses to national economies. In 2011, insured losses from natural disasters reached an all-time high and impacts are predicted to worsen with climate change and population growth. The proportion of the world's GDP annually exposed to tropical cyclones has increased from 3.6 percent in the 1970s to 4.3 percent in the first decade of the 2000s (UNISDR 2011). Insurers have paid more than $300 billion for coastal damages from storms in the past 10 years, which often goes toward rebuilding similar coastal infrastructure that is still vulnerable to coastal storms and flooding.

Coastal and marine habitats, particularly coral reefs and mangroves, can substantially reduce exposure and vulnerability, providing natural protection from risk. Yet the value of these systems as "green infrastructure" is still not fully recognized, and they continue to be lost and degraded. The *Global Assessment Report on Disaster Risk Reduction* highlights that economic loss risk because of tropical cyclones and floods is growing as exposure of economic assets increases and the status of ecosystem services degrades (UNISDR 2011), and that societies are excessively discounting risk in development choices, particularly in coastal areas (UNISDR 2015). In terms of habitat loss statistics, 30 to 50 percent of wetlands have already been lost (Zedler and Kercher 2005), 19 percent of mangroves were lost from 1980 to 2005 (Spalding et al. 2010), and 75 percent of the world's coral reefs are now rated as threatened (Burke et al. 2011).

The trends in habitat loss and the concomitant loss of coastal protection services will continue unless the values of these habitats are accounted for in policy and decisions. The importance of mainstreaming the coastal protection value of mangroves and reefs is great, as there are substantial opportunities and risks that will affect the ecosystems and the communities that rely on their services over the next 5 to 10 years. Sixty percent of the world population is expected to live in urban areas by 2030, with a greater concentration in coastal areas. As coastal development increases, there will be heavy investments in coastal infrastructure and the potential loss of more coastal habitats and their services.

Billions of dollars are being dedicated to reduce risks from disasters and climate change, creating both threats and opportunities for natural systems. Total Fast Start Finance commitments under the UNFCCC (through 2012) include roughly $3 billion for climate adaptation assistance. In the United States, FEMA spends $500 million per year to reduce flooding hazards. Middle-income countries, such as Brazil, China, and Colombia, are making multibillion dollar investments to address risks of flooding and other disasters exacerbated by climate change. Most of these funds are destined for the creation and maintenance of "grey infrastructure," such as seawalls, which will further degrade coastal ecosystems, and may not be cost effective for risk reduction when compared to more natural and hybrid alternatives.

Following the 2004 Indian Ocean tsunami and Hurricane Katrina in 2005, there has been substantial scientific focus on recognizing and quantifying the benefits from mangroves and coral reefs. There has also been an increasing focus on identifying the policies needed to encourage ecosystem protection and restoration, specifically for hazard mitigation and risk reduction.

1.1| Wealth Accounting and Valuation of Ecosystem Services (WAVES)

Wealth Accounting and Valuation of Ecosystem Services (WAVES), which is a global partnership led by the World Bank, aims to promote sustainable development by mainstreaming natural capital in development planning and national economic accounting systems (the System of

National Accounts, or SNA), based on the System of Environmental-Economic Accounting (SEEA). This global partnership (www.WAVESpartnership.org) brings together a broad coalition of governments, UN agencies, nongovernmental organizations, and academics for this purpose.

Eight developing countries—Botswana, Colombia, Costa Rica, Guatemala, Indonesia, Madagascar, Philippines, and Rwanda—are currently partnering with WAVES to establish natural capital accounts. More are expected to join during the next two years. These accounts include experimental accounts for ecosystems and ecosystem services, and mangroves have been identified as a priority ecosystem for some countries. The methodology for measuring and valuing the provisioning and tourism services of mangroves and reefs are well established and these values are, in principle, included in the national economic accounts. But methodology for including these regulating services in national economic accounts, notably, coastal protection services, fisheries enhancement, and carbon storage, is still in an experimental stage and there is not yet international agreement on their measurement. Guidance is needed for countries that want to build comprehensive accounts for mangroves and reefs that include all these services.

The WAVES' Policy and Technical Experts Committee (PTEC), which was established in the fall of 2012, has a mandate to guide the development and implementation of scientifically credible methodologies for ecosystem accounting, identify opportunities to contribute to policy and mainstreaming; and ensure cohesion, consistency, and scalability among the country studies. This guidance note has been developed under PTEC.

1.2| Process for Developing the Guidance Note

This guidance note provides review and recommendations for how the protective services of mangroves and coral reefs can be included in national wealth accounts and other decision-making processes to support planning for development, disaster risk, and coastal zone management. As part of this effort, several extensive reviews synthesize evidence of the role mangroves (Chapter 2) and coral reefs (Chapter 3) play in coastal protection and risk reduction. It also reviews the tools and approaches commonly used by ecologists, economists and engineers for estimating the coastal protection services of coastal habitats (Chapter 4). Moreover, it examines how how the valuations of these coastal protection services can be considered in the System of Environmental Economic Accounts (SEEA), the satellite accounts to the System of National Accounts (SNA) (Chapter 5). Finally, it provides recommendations for advancing the assessment and the use of coastal protection values from coral reefs and mangroves in national and regional decisions (Chapter 7). The recommendations identify the critical needs and opportunities in (i) data, (ii) models and methods, (iii) building support, and (iv) actions for advancing the assessment and the incorporation of coastal protection values from coral reefs and mangroves in making decisions. These recommendations are synthetic and targeted to decision makers.

These chapters and recommendations were reviewed and developed with input from 20-plus experts who participated in a review and synthesis workshop convened December 3–5, 2014. Following the workshop, additional experts reviewed the updated chapters. All of the reviewers are noted in the acknowledgements.

1.3| How to Use the Information

The guidance note aims to provide information, tools, and approaches for valuing the coastal protection provided by reefs and mangroves. This information is intended to be useful first for testing in the System of Environmental Economic Accounts-Experimental Ecosystem Services (SEEA-EEA).

The note provides extensive review of the evidence for coastal protection from mangroves and reefs and discusses how that has already been influential in policy and practice. In addition to helping with economic accounting, this information is expected to be useful for incorporating natural coastal protection services in other decision-making processes, including habitat restoration, coastal zoning, development planning, and disaster risk management. It is anticipated that this note can help further bridge the gaps between environment and disaster risk management by highlighting where natural coastal protection approaches can be used by planners, managers and policy makers across these sectors. This note also identifies key information gaps that should be the focus of future efforts in research and data collection (for example, nearshore bathymetry).

1.4| Limitations and Cautions

Research on natural coastal protection benefits has advanced tremendously particularly in the past 10 years following Hurricane Katrina and the Indian Ocean tsunami and with the growing interest in ecosystem-based adaptation and risk reduction. Much of the science and many of the practices (for example, restoration projects) are relatively new. The authors of this note expect significant growth and debate to remain concerning natural coastal protection. The recommended models and tools, particularly those from the engineering and insurance sectors, are robust and their use for ecosystems requires few, if any, modifications. However, there will be continued growth in understanding of the particular conditions (for example, storm direction and intensity and ecosystem rugosity) under which ecosystems succeed and fail to provide protection. Data gaps, particularly in bathymetry and coastal assets, are critical to address. These limits affect all assessments of coastal risk and risk reduction strategies, including natural coastal protection.

2| Coastal Defense Services Provided by Mangroves

Anna McIvor,[a,b] Tom Spencer,[a] Iris Möller,[a] and Mark Spalding[a,b]

2.1| Summary

Mangrove forests reduce risk from coastal hazards, such as waves, storm surges, and tsunamis. They reduce flood depths and wave heights, lessening damage to property behind mangrove forests. The level of risk reduction depends on the type of hazard, as well as mangrove characteristics. For wind and swell waves, wave height can be reduced by 50 to 100 percent over 500 meters of mangrove forest. Mangrove species with dense vegetation are most effective at reducing wave height. With respect to storm surges, water level measurements and numerical models show that a one kilometer wide mangrove forest can reduce storm surge peak water levels by 5 to 50 centimeters. This variation depends on the forward speed of the surge and the presence of channels and pools within the mangroves, which allow water to flow through more easily. Tsunami water depths can be reduced by up to 30 percent over approximately 500 meters of mangroves, and this is likely to depend on the density of mangrove vegetation, as well as tsunami characteristics. However, mangroves can also be damaged or destroyed by tsunamis and hurricanes/cyclones/typhoons and their associated storm surges, making them less able to reduce risk from these hazards.

2.2| Introduction

Mangrove forests occur along tropical and subtropical coasts, with an estimated global coverage of around 152,000 square kilometers. They are found in 123 countries, usually along low-energy coastlines and in embayments and coastal lagoons. Mangroves provide a variety of ecosystem services to adjacent coastal populations, such as providing food and timber, as well as coastal defense services by reducing risk from coastal hazards.

Societies need to understand this coastal defense service of mangroves in order to account for it and ensure its inclusion in coastal decision making. This is particularly necessary where there are competing land uses, such as aquaculture and agriculture, which could result in the destruction of mangroves and increase risk from future coastal hazards. Such land-use changes have been occurring for many decades and are ongoing in many areas, with mangrove forests being converted to alternative uses that may seem more profitable in the short term. However, the long-term costs of these choices may far outweigh the short-term benefits.

This chapter reviews the evidence for the coastal defense services that mangroves provide. It draws together available data in order to understand both what mangroves can contribute to coastal risk reduction and what their limitations are in this respect. It focuses on three coastal hazards: wind and swell waves, storm surges, and tsunamis. It then explores how much these hazards are reduced by mangroves, and what factors influence the level of reduction. It also briefly considers whether mangroves can provide a sustainable form of coastal defense into the future.

2.3| Wind and Swell Waves

Although mangrove forests are usually found on shores with little incoming wave energy, they may receive larger waves during storms, cyclones (also called hurricanes and typhoons), and periods of high winds. Some common mangrove trees—such as the red mangrove, *Rhizophora*—have aerial roots, which help to prop the trees up in the soft sediments where they often grow (shown

[a] University of Cambridge.
[b] The Nature Conservancy.

Figure 2.1: Factors Affecting Wave Attenuation through Mangroves

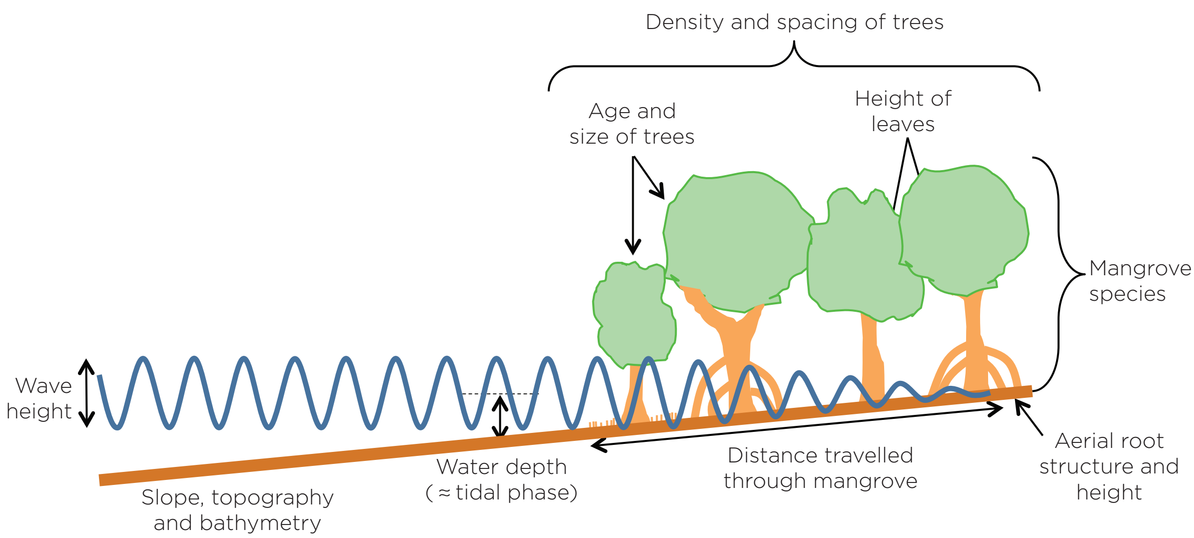
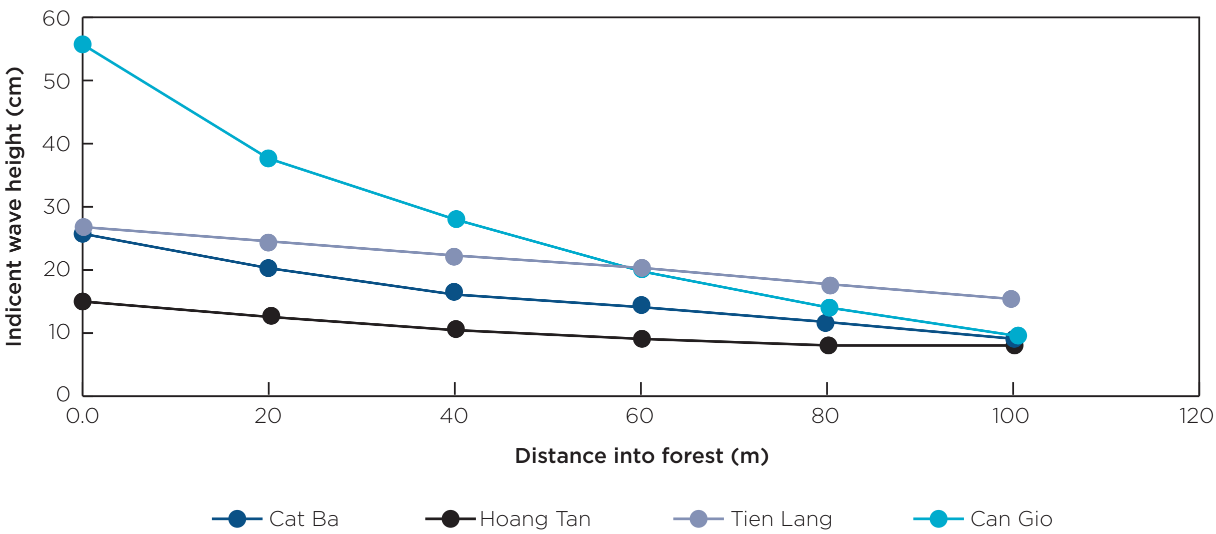


Figure 2.2: Variation in Wave Height with Distance Travelled through Mangrove Forests in Four Sample Locations in Vietnam (adapted from Bao 2011)



schematically in Figure 2.1). These aerial roots act as obstacles to the passage of wind and swell waves, and result in these waves being reduced in height as they pass through the mangrove area.

Wave attenuation (that is, wave height reduction) through mangroves has been studied in a number of locations. Studies suggest that mangroves can reduce the height of wind and swell waves over relatively short distances (summarized in Table 2.1). Measured rates of wave-height reduction vary between 13 and 66 percent over 100 meters of mangroves, or 50 and 100 percent over 500 meters of mangroves, based on data in Mazda et al. (2006) and Quartel et al. (2007) (Table 2.1).

The highest rate of wave height reduction per unit distance occurs near the mangrove edge, as waves begin their passage through the mangroves. Wave height declines exponentially with distance through mangroves (Figure 2.2; Bao 2011).

Table 2.1: Wave Attenuation Studies in Mangroves

Type of study	Location of study	Wave characteristics	Mangrove characteristics	Magnitude of wave attenuation
Time series of water surface elevation and flow along transects (Brinkman et al., 1997; Massel et al., 1999)	Cocoa Creek, Australia and Iriomote Island, Japan.	Cocoa Creek: wave periods between 1.5 and 4.5 s. Iriomote Island: most wave energy occurred in waves with periods of 1.5 to 3s.	*Rhizophora stylosa* was the dominant mangrove species at Cocoa Creek, Bruguiera at Iriomote Island.	The wave energy transmission factor varied between 0.45 and 0.8 (where 1 is no loss of wave energy) 150 m into the forest.
Water levels and current velocities measured at several stations (Mazda et al., 1997a)	Tong King delta, Vietnam.	Swell waves with periods of 5 to 8 s.	Areas planted with *Kandelia candel* or *Sonneratia caseolaris*	Rate of wave height reduction up to 20% per 100m of mangroves (6 year old Kandelia candel trees that had been planted). Young mangroves (2 month old Sonneratia caseolaris) did not reduce waves.
Water levels measured (Mazda et al., 2006)	Vinh Quang coast in northern Vietnam.	Swell waves with periods of 8–10 s from a typhoon, maximum wave height approximately 40 cm.	Mangrove forests were made up of *Sonneratia* sp.	Rate of wave height reduction varied between 0.0014 and 0.0058 per m cross-shore. The rate of wave reduction over 100 m of mangrove forest was calculated as 45% when water depth was 0.2 m and 26% when the water depth is 0.6 m.
Current velocity and water level measured at three stations. Wave reduction was compared over mangrove area and area with a sandy surface and embryonic cheniers (Quartel et al., 2007)	Red River Delta, Vietnam.	Wave periods 3.5–6.5 s.	*Kandelia candel* was the dominant mangrove species	Wave height reduction varied between 0.002 and 0.011 per metre cross-shore. The measured wave height reduction in the mangrove was higher than over the sandy surface.

(*continued on next page*)

Table 2.1: Wave Attenuation Studies in Mangroves *(continued)*

Type of study	Location of study	Wave characteristics	Mangrove characteristics	Magnitude of wave attenuation
Pressure sensors and wave gauges placed along a transect (Vo-Luong & Massel, 2006, 2008)	Nang Hai, Can Gio mangrove forest, southern Vietnam.	A wave period of 1.2 s is assumed in the numerical model of wave reduction at this site. Incident wave heights were 0.35–0.4 m.	Forest consisted of mixed mangroves of Avicennia sp. and *Rhizophora sp.* in the first 100m; behyond this *Rhizophora sp.* dominated. There was a sharp drop in the level of the substrate at the edge of the mangroves (approx. 1.4m).	50–70% of the wave energy was dissipated in the first 20 m of mangrove forest when the water level (measured from the area without mangroves) was 1.9 and 2.1 m deep; 50% was dissipated over 40 m when water level was 2.5 m deep. After this initial drop, wave height continued to decrease only slightly.
Wave height measured at 6 points along 120m transects from forest edge; measurements from 32 plots spread between 2 locations (Bao, 2011)	The Red River Delta (northern Vietnam) and Can Gio mangrove forest (southern Vietnam).	Initial wave heights between 20 to 70 cm (wave periods not given).	Six mangrove species present.	Mean wave height reduction (calculated using data from graphs in Bao, 2011) was 0.0054/m over 80m of mangrove forest.
High frequency pressure sensors along transects (Horstman et al., 2014)	Mangroves fringing estuaries in the southern Andaman region of Thailand	In December, most wave energy was present in waves with periods 3–5s and 6–11s; in April/May, most energy present in waves with periods 6–10s and 11–19s.	*Avicennia, Sonneratia* and *Rhizophora* species present.	Wave attenuation rates between 0.002/m in sparesely vegetated forest fringes with Avicennia and *Sonneratia* up to 0.012/m in dense *Rhizophora* vegetation at the back of the forests.

Factors affecting wave height reduction

A number of factors affect the rate of reduction of wave height with distance through a mangrove forest, such as the density of vegetation, the presence of aerial roots (only present in some mangrove species), the underlying topography, the height and period of the incoming waves, and the water depth. The water depth influences the type of vegetation that waves are passing through (aerial roots, trunks, or branches) (Figure 2.1).

Vegetation structure and water depth: The physical structure of the trees influences the vegetation density at different heights above the ground. As a result, wave attenuation rates depend on the water depth (which, in turn, depends on the tidal level), as this affects the height of the water and, hence, where the waves reach in relation to the structure of the mangrove vegetation.

For example, *Rhizophora* species have large prop roots, which form a dense network above the soil surface (Figure 2.3a). These prop roots are expected to rapidly absorb the energy of waves passing through them. Above the prop roots, the trunks present less of an obstacle to waves, allowing them to pass through more easily. This results in high wave attenuation at shallow water depths (that is, low transmission of waves through mangroves), and then a reduction in wave attenuation (increase in wave transmission) as the water becomes deeper and the waves are less affected by the prop roots (Figure 2.3a).

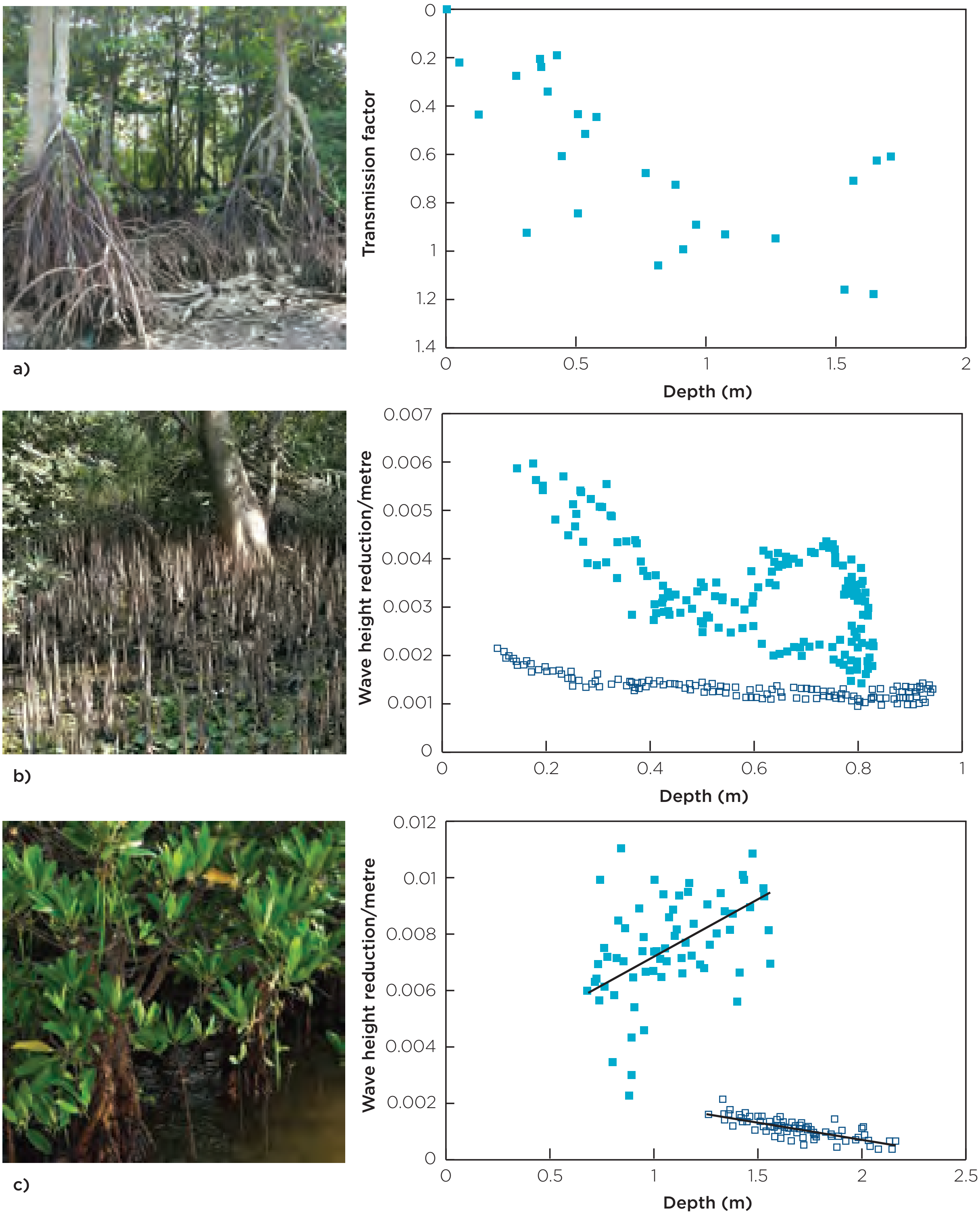
While smaller than the prop roots of *Rhizophora* species, the pneumatophores of *Sonneratia* (Figure 2.3b) and *Avicennia* also act as obstacles to water movement at shallower depths, causing high wave attenuation at these depths. Mazda et al. (2006) measured wave attenuation in a mangrove forest created by planting *Sonneratia* in northern Vietnam. They found the highest attenuation at shallow depths, and lower wave attenuation as water levels rose (Fig. 2.3b), until the water levels reached the height of the branches and leaves, when wave attenuation increased again as the thickly spread branches and leaves dissipated the wave energy (Mazda et al. 2006).

Mangrove species without aerial roots, such as *Kandelia candel*, are less able to reduce wave heights at shallow water depths, but are more effective at higher water depths, when the waves reach the branches and leaves. This can be seen in Figure 2.3c, which shows waves passing through *Kandelia candel* in the Red River Delta, Vietnam (Quartel et al. 2007). Here the rate of wave reduction increased with water depth, as the waves passed through the denser vegetation higher up (Figure 2.3c).

Characterizing mangrove vegetation in relation to wave height reduction: The "projected area" of mangrove vegetation (equivalent to the silhouette of the vegetation, as seen from the direction of oncoming waves) can be used to calculate the drag coefficient, a measure of the vegetation's effectiveness at reducing wave height. Measurements of mangrove trunk height, width and density, as well as foliage height and width, can be used to estimate the projected area of vegetation to waves approaching in different water depths. The drag coefficient C_D can be calculated from measured reductions in wave height. A comparison of the drag coefficient with the projected area of mangrove vegetation for waves passing through *Kandelia candel* showed that the drag coefficient could be approximated by the function $C_D = 0.6\ e^{0.15A}$, where A was the projected cross-sectional area of the underwater obstacles up to a certain water depth (Figure 2.4; Quartel et al. 2006).

Initial wave height: The rate of wave height reduction depends on the initial wave height; large waves were attenuated more per unit distance (Figure 2.5).

Figure 2.3: Wave Attenuation through Three Mangrove Species



a) Left: Prop roots of *Rhizophora mucronata* (photo by Carmen LaCambra). Right: The transmission of wave energy plotted against water depth in a mangrove forest dominated by *Rhizophora stylosa* at Cocoa Creek, adapted from Brinkman et al. (1997). (A low transmission factor shows high wave attenuation. The y-axis has been reversed so that the pattern can be compared with the other graphs.) b) Left: Pneumatophores of *Sonneratia alba*, Bangkok, Thailand. (Photo by Tony Rodd, used under the Creative Commons license.) Right: Wave height reduction plotted against depth in a mangrove forest dominated by *Sonneratia* sp. (mangrove forest (■) and area without mangroves (■), data from Mazda et al. 2006). c) Left: *Kandelia candel*. (Photo by Vineeth Vengolis, used under the Creative Commons license.) Right: Wave height reduction in a forest dominated by *Kandelia candel* (mangrove forest (□) and area without mangroves (□), data from Quartel et al. 2007).

Figure 2.4: Variation of the Drag Coefficient (here called the resistance coefficient) with the Projected Area of Obstacles (that is, mangrove vegetation) to Incoming Waves for *Kandelia candel* in the Red River Delta, Vietnam (data from Quartel et al. 2007)

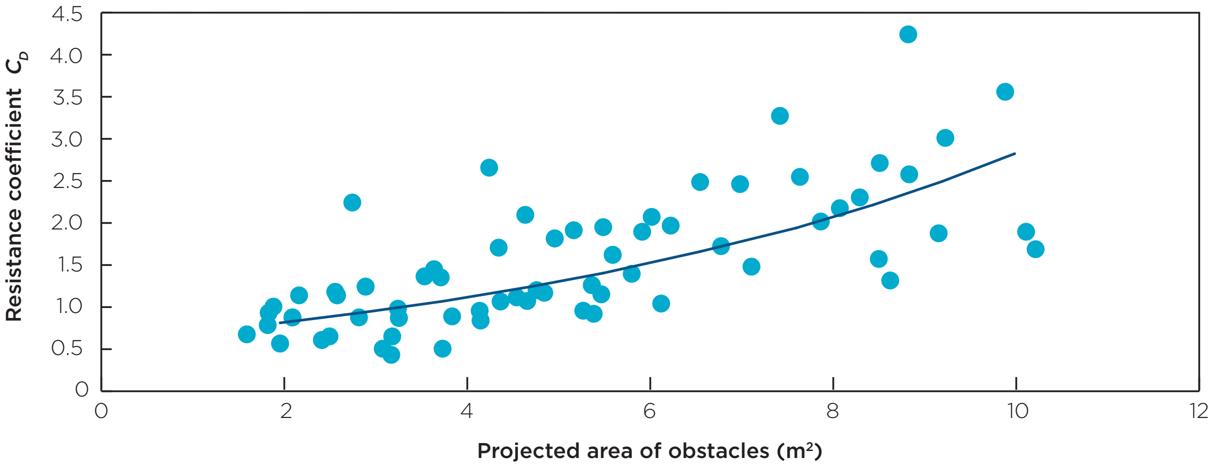
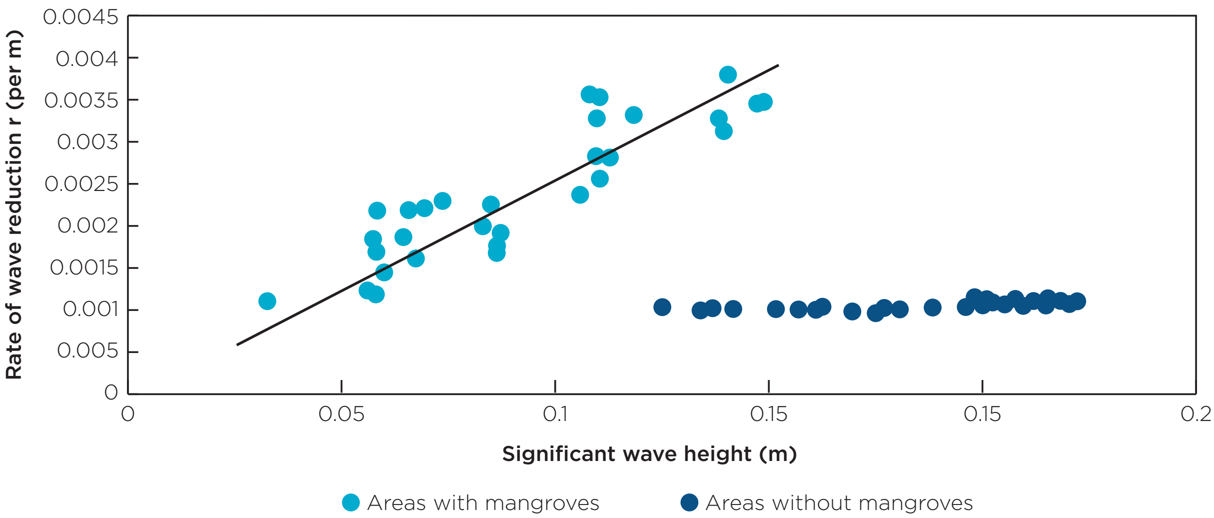


Figure 2.5: Variation of Wave Attenuation with Significant Wave Height (the mean height of the highest third of the waves) in Areas with and without Mangroves (*Sonneratia spp.* in Vietnam, data from Mazda et al. 2006)



(Measurements were taken over a three-hour period, during which water depth remained constant. In the area without mangroves, wave reduction was independent of the significant wave height.)

Other factors affecting wave attenuation: Other factors that will affect the rate of wave attenuation within mangroves include the underlying topography, wave period, and tidal flows. While mangroves are usually found on very gently sloping shores, tidal channels and erosive "cliffs" at the edge of mangroves will influence wave propagation through the mangrove areas. Cliffed margins can increase wave height behind the margin, as seen in salt marshes; wave height is then subsequently reduced as the waves pass through the vegetation (Möller and Spencer 2002). The mangrove vegetation will also lower wind speeds over the water surface, reducing the likelihood of waves increasing in height within mangrove areas.

Reduction of surface winds by mangroves

Mangroves buffer the water surface from the effects of wind, thereby reducing the generation of wind waves, which can make a substantial contribution to water levels and damage. However, wind and swell waves mostly originate from the effect of wind on the water surface outside the mangrove area. By reducing wind speeds over the water surface within the mangrove area, wind waves do not increase in height in this area (and they are usually reduced due to the presence of the mangrove obstacles).

Modeling wind and swell waves through mangroves

To understand the level of protection provided by mangroves and to plan how to increase it, coastal engineers have numerically modeled the passage of waves through mangroves using a standard wave model within SWAN (Simulating WAves Nearshore; Suzuki et al. 2011), as well as a model developed specifically for waves in mangroves called WAPROMAN (for WAve PROpagation in MANgrove Forest; Vo-Luong and Massel 2008).

These models require knowledge of the mangrove characteristics, the wave parameters, and the local bathymetry and topography (that is, the slope of the seabed and land). The predictions of both models matched observed wave data reasonably well. However, the models have only been tested against data from one location in Vietnam. Further validation is needed to increase confidence in their ability to predict wave attenuation in other locations, under different combinations of the controlling factors identified above (for example, with different mangrove species or topography).

The SWAN model has been used to simulate waves passing through a mangrove island in front of a port in Orissa, India (Narayan et al. 2010). Such simulations can increase our understanding of the coastal defense functions currently provided by mangroves and can guide the management and restoration of mangroves as part of an integrated coastal defense strategy.

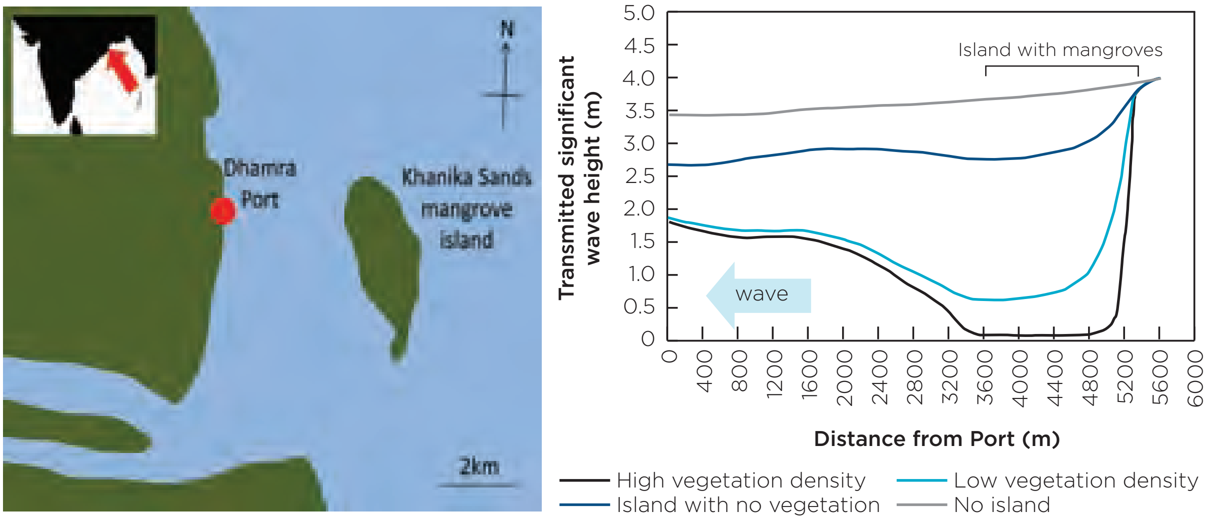
Bao (2011) has developed a statistical model to explore the relationship between some standard forest measurements (tree height, tree density, and canopy closure) and wave attenuation with distance. The model was able to predict wave reduction within the Vietnamese mangroves for which it was developed, and could be used to determine the width of mangrove belt needed to deliver a predefined level of protection from waves. While this approach shows promise for use by nonexperts at the local level, it currently relies on extrapolating wave attenuation data beyond measured wave heights and has only been tested in Vietnamese mangroves.

A case study demonstrating how mangroves can be used to reduce waves

The following case study provides an example of how mangroves can be managed to ensure maximum wave reduction at a port in India.

Narayan et al. (2010) used the SWAN model (as modified by Suzuki et al. 2011) to explore the effect of a mangrove island (Kanika Sands mangrove island, Orissa, India) on waves reaching Dhamra port, which lies behind the island (Figure 2.6). Their analysis showed that for cyclone induced wind and swell waves four meters in height, which are expected to have a return period of 25 years at a distance of five kilometers from the port (that is, waves of this height are expected to occur, on average, once every 25 years), wave height at the port would be reduced to less than two meters by the presence of the mangrove island, assuming the waves were approaching the port at a 90º angle (Figure 2.6). They also estimated that at the port, 2.5 meters high waves have a return period of 60 years, compared with a return period of 20 years, if the mangrove island were not present (that is, the mangrove island reduces the likelihood and frequency of large waves reaching the port).

Figure 2.6: Demonstration of How Mangrove Coastal Defense Services can be Calculated using Appropriate Numerical Models



Left: Dhamra Port and Khanika Sands mangrove island on the coast of Orissa, India. Adapted from Narayan (2009). Right: The transmitted wave heights (Hs = significant wave height) at different distances from the port for two different vegetation densities, compared with cases where there is no vegetation or no island, for waves with a return period of 25 years. Reproduced with permission, from Narayan (2009).

Narayan et al. (2010) also used the model to explore the effects of managing mangroves for coastal risk reduction (for example, using engineering approaches to extend the island and its mangrove cover). They concluded that an extension of the island and its mangrove vegetation on the northern side of the island would further decrease wave height at the port.

This example demonstrates how the current coastal defense services provided by mangroves can be calculated using appropriate numerical models, and how these models can be used to determine which forms of mangrove management would be most effective at reducing risk from large wind and swell waves during storms.

Summary: Wind and Swell Waves

All studies have found that mangroves are able to attenuate wind and swell waves. Over a 100-meter-wide mangrove belt, mangroves can reduce wave height by 13 to 66 percent, while over a 500-meter-wide mangrove belt, they can reduce wave height by 50 to 100 percent. Most studies have measured the attenuation of relatively small waves (wave height below 70 centimeters), and further research is needed to measure the attenuation of larger wind and swell waves (for example, during cyclones, when much larger waves can be present and when protection from waves is most important).

Wave-height reduction within a mangrove forest depends on the width of the forest, mangrove tree morphology, water depth, topography, and wave height. Mangrove species with aerial roots are more effective at attenuating waves in shallow water, when the waves encounter the roots; species without aerial roots are better able to attenuate waves when the water level reaches the branches.

2.4| Storm Surges

Cyclones cause storm surges when high winds and low atmospheric pressure combine to increase water levels at the coast, resulting in seawater flooding onto the land. Storm surges can reach several meters in depth. For example, in 1991 a cyclone with a maximum recorded wind speed of 225 kilometers per hour created a seven-meter-high storm surge in the southwestern part of Bangladesh, resulting in the loss of 138,000 lives (Bern et al. 1993; Matsuda 1993).

Cyclones and the storm surges they produce can be a major threat to low-lying coastal areas and their inhabitants in the areas where they occur (mostly the eastern margins of continents in tropical and subtropical areas, as such storms tend to travel to the western boundaries of oceans). They can result in extensive flooding, loss of life, and damage to property. Global climate change may result in increased storm surge flooding in some areas, through intensification of the cyclones driving the storm surges and as a result of sea-level rise (Mousavi et al. 2011; Lin et al. 2012).

Under some circumstances, mangroves can reduce damage and loss of life caused by storm surges by reducing flood depths and reducing the height and energy of wind and swell waves riding on the surface of the surge (as discussed in the previous section). Evidence for the ability of mangroves to reduce storm surge flood depths and associated damage comes from three sources: direct observations of water heights; the use of well-validated numerical models that simulate storm surge behavior in the presence or absence of mangroves; and observations of the damage caused and the number of lives lost from storm surges. Table 2.2 lists available studies (reviewed in McIvor et al. 2012b).

Measured rates of peak water level reduction through mangroves range from four to 48 centimeters reduction per kilometer of mangrove width, based on empirical measurements (4.2 and 15.8 centimeters/kilometer; Krauss et al. 2009), and validated numerical models (up to 48 centimeters/kilometer; Zhang et al. 2012). However, very few data are available because of the difficulties associated with measuring water levels during storm surges. All data currently available are from the southeastern United States, where networks of recorders are in place in wetland areas. Numerical models and simulations, validated using these data, provide a means of exploring the importance of different factors in reducing storm surge water heights.

While measurements of peak water level reduction rates through coastal wetlands are often quoted as a certain number of centimeters of water level reduction per meter of inland distance, such constant attenuation rates imply a linear reduction in water level with distance into the mangroves (i.e., mangrove width). This is rarely true because the landscape is usually heterogeneous (i.e., it is usually a mixture of channels, pools and vegetation with a varied topography), and because the underlying rate of reduction varies with distance travelled through the mangrove (described below). Consequently, such peak water-level reduction rates should be regarded with caution. At best, they may serve as rules of thumb with a high degree of scatter (Resio and Westerink 2008; Wamsley et al. 2010).

Zhang et al. (2012) used simulations based on a validated numerical model to explore the effects of different widths of mangroves. They found that the largest reduction in peak water levels occurred at the seaward edge of the mangroves, while further inland the water level changed more slowly (Figure 2.7). They suggest that this might explain the relatively low rates of peak water level reductions measured in the field by Krauss et al. (2009; Table 2.2). These measurements started some distance into the mangroves, and the water level reduction in the most seaward mangroves might have been higher.

Zhang et al. (2012) note that peak water levels in front of (seaward of) mangroves are increased by the presence of mangroves, as a bulge of water forms behind the additional resistance to flow provided by the mangroves.

Table 2.2: Studies on the Effect of Mangroves on Storm Surge Peak Water Levels and Storm Surge Impacts

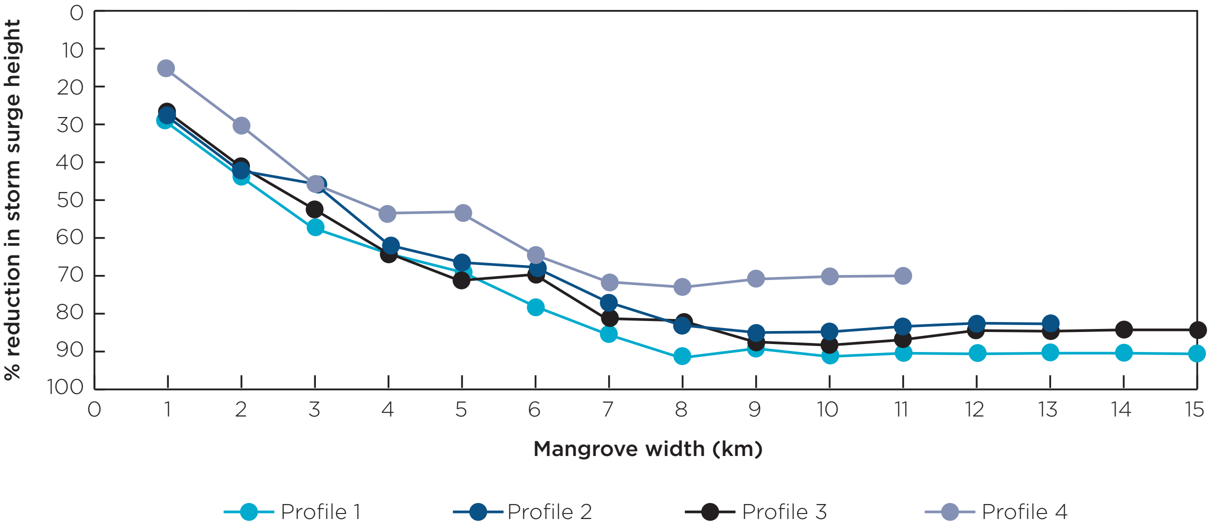
Type of study and source	Location	Cyclone	Vegetation studied	Storm surge peak water level reduction or impact reduction through mangroves
Empirical observations				
Water levels recorded within a mangrove/marsh area during a hurricane (Krauss et al., 2009)	Ten Thousand Islands National Wildlife Refuge, Florida, USA	Hurricane Charley, a category 4 hurricane, 13 August 2004, with maximum sustained winds of 240 km/hr at landfall.	Mangrove/interior marsh community; in mangrove area, dominant species was *Rhizophora mangle*	Peak water level height reduction of 9.4 cm/km across all recording points, which included salt marshes and mangroves; 15.8 cm/km in mangrove area. Measured over 4 points approx. 1 km apart and in line with each other, laid out in a landwards direction; area between 1st two points was mangrove, other areas were salt marsh.
Water levels recorded within a mangrove area during a hurricane (Krauss et al., 2009)	Along the Shark River (Everglades National Park) in south western Florida, USA	Hurricane Wilma, a category 3 hurricane, 24 October 2005.	Riverine mangrove swamp, dominant species is *Rhizophora mangle* (Chen and Twilley, 1999)	Peak water level height reduction of 4.2 cm/km across all 3 recording points; –0.2 cm/km between lower pair of recorders due to river water backing up, 6.9 cm/km between upper recorders, with recorders placed 50–80m from the river's edge at river-kms 4.1, 9.9 and 18.2.
Numerical models and simulations				
One-dimensional, nonlinear, long wave differential equation (Tanaka, 2008; ITJSCE, 2008)	Mathbaria, south-western coast of Bangladesh	Cyclone Sidr, 15 November 2007, maximum wind speed 250 km/hr, water levels raised by about 4 m (ITJSCE, 2008).	Forested area, approximately 150 m in width, non-mangrove species *Casuarina equisetifolia*.	The model suggested that vegetation had little effect on storm surge peak water levels over 150m of forest. When wind waves with a period of 1 or 2 minutes were included on top of the storm surge, the water depth behind the vegetation was reduced by 120 or 280 mm respectively (compared to no vegetation being present). When the ground slope in the model was reduced from a 1 in 100 gradient to a 1 in 500 gradient, the presence of vegetation reduced maximum water levels by 0.8 m (long wave period 2 h and short wave period 2 min). Model results broadly matched field observations.

(*continued on next page*)

Table 2.2: Studies on the Effect of Mangroves on Storm Surge Peak Water Levels and Storm Surge Impacts *(continued)*

Type of study and source	Location	Cyclone	Vegetation studied	Storm surge peak water level reduction or impact reduction through mangroves
An unstructured Eulerian-Lagrangian Circulation (ELCIRC) model (Xu et al., 2010, using the model of Zhang et al., 2004)	Biscayne Bay, east coast of Florida, USA	Hurricane Andrew, 24 August 1992, peak wind speed 227 km/hr, maximum storm tide 5.2 m	Coastal mangrove zone 1 to 4 km wide with tree heights of 1 to 20 m. Species present *Rhizophora mangle* and *Avicennia germinans* (Smith et al., 1994).	The model was used to explore the effects of land cover types on flood extent. Land cover types, including mangroves, were incorporated into the model using Manning's coefficient as a measure of surface roughness. Modeled surge inundation extents most closely matched observed debris lines when Manning's coefficient was set to 0.15 in mangrove areas. The authors concluded that spatial variation in surface roughness due to vegetation can significantly influence local inundation patterns during storm surges.
Coastal and Estuarine Storm Tide (CEST) model (Zhang et al., 2012; Liu et al., 2013)	Gulf Coast, Florida, from Sanibel West to Key West, USA	Hurricane Wilma 24 October 2005, with max winds of 195 km/hr, peak water level 5 m.	Dominant species *R. mangle, Laguncularia racemosa, A. germinans*. Trees 4 to 18m high, stem diameters 5 to 60cm. Mangrove width 6 to 30 km.	Model suggested a peak water level reduction of between 23 and 48 cm/km through the mangrove area. Results were validated with recorded water levels. Model used 0.14 as Manning's coefficient in mangrove areas. Highest rates of peak water level reduction per unit distance through mangroves occurred near seaward edge of mangroves (see discussion in text).
Statistical analyses of loss and damage				
Regression methods to estimate single-equation count-data models (poisson and negative binomial) relating the number of deaths to mangrove width (Das and Vincent, 2009; see also Baird et al., 2009; Vincent and Das, 2009)	Kendrapada District, Orissa, India	Odisha supercyclone that struck the eastern coast of India in October 1999, with a 6 m storm surge.	409 villages were classified as being fronted by mangroves when the cyclone occurred, or mangroves having been present historically (1944) but no longer present in 1999.	Villages with wider mangroves between them and the coast had significantly fewer deaths than villages with narrower mangrove belts or no mangroves. The model predicted that there would have been 1.72 additional deaths per village within 10 km of the coast if mangroves had not been present. Mangroves saved fewer lives than an early warning issued by the government, which saved 5.84 lives per village; however mangroves helped to further reduce the death toll amongst those who did not evacuate. The statistical model controlled for variables such as distance to coast and height of storm surge.

Figure 2.7: Reduction of Storm Surge Height by Mangroves on the Gulf Coast of South Florida, United States during Hurricane Wilma (2005, Category 3 on impact), Modeled using CEST (data from Zhang et al. 2012)



Factors affecting storm surge reduction in mangroves

Storm surge reduction through mangroves is expected to depend on a number of factors: (i) mangrove vegetation characteristics, such as forest width, tree density, and structural complexity (roots, stems, branches, and foliage) of the dominant species or mix of species; (ii) physical characteristics, such as the presence of channels and pools; (iii) the topography of the area (both are influenced by mangroves over the longer term); and (iv) storm characteristics, such as the size and forward speed of the cyclone, which may interact with mangroves to influence storm surge reduction.

i. **Mangrove vegetation characteristics:** The density of mangrove vegetation is expected to affect the ability of mangroves to reduce storm surge water levels (Krauss et al. 2009; Alongi 2008). However, little field information is available to support this assumption. Mangrove vegetation characteristics (Mazda et al. 1997b) affect tidal flows, which are relatively similar to storm surge flows, so it is highly likely that the structure, density, and volume of mangrove vegetation will also affect storm surge flows and peak water levels.

ii. **The presence of channels and pools within mangrove areas:** The presence of channels and pools within a mangrove area is likely to decrease their capacity to reduce peak water levels, because the water is able to pass more easily along these channels and penetrate further inland more quickly (Krauss et al. 2009; Zhang et al. 2012); the same effect has been reported for fragmented salt marshes (Loder et al. 2009). Based on storm surge simulations validated with field data, Zhang et al. (2012) found that surge height decreased at a rate of 23 centimeters/kilometer through an area with a mixture of mangrove islands and open water, while in areas with less open water, surge height reduction rates ranged from 40 to 48 centimeters/kilometer.

iii. **Topography:** Topography is the most important local factor affecting inundation from storm surges, interacting with the peak water level to influence the extent of inundation. Mangroves affect local topography over the longer term through their effect on sedimentation, erosion, and the maintenance of tidal creeks and channels (Spencer and

Moller 2013; McIvor et al. 2013). These channels and the levees that form around them increase topographic roughness, thereby increasing drag on water flows, and potentially reducing storm surge water levels.

iv. **The size and speed of the cyclone and storm surge:** The numerical model of Zhang et al. (2012) suggests that mangroves are more effective at reducing the water levels of fast moving surges than those of slow moving surges. The water levels within slow-moving surges are likely to be relatively unaffected by the presence of mangroves, as the water has time to flow through the mangroves. For example, Zhang et al. (2012) found that the south Florida mangroves could be expected to protect the area behind them against flooding from a Category 5 hurricane with a rapid forward speed of 11.2 meters/second, but not from a Category 5 hurricane with a slow forward speed of 2.2 meters/second, based on simulations (Table 2.2). They estimate that a mangrove forest with a width of tens of kilometers would be needed to attenuate a two- to three-meter storm surge from a slow-moving Category 5 hurricane.

Storm surge reduction by mangroves also depends on initial surge height and surface wind speeds, because very large surges and very high wind speeds can damage mangroves, rendering them less effective at reducing water levels. The damage caused to mangroves is described below.

Reduction of surface winds by mangroves

Mangroves may also reduce storm surges through wind reduction. Forest canopies modify wind speeds as shown in a study of wind speeds around mangrove plantations in Sanjiang Bay in Haitian Province, South China (Chen et al. 2012). Canopies reduced mean wind speeds up to five meters/second by more than 85 percent, and when the mean wind speed was greater than 15 meters/second, wind speeds were still reduced by more than 50 percent.

While it is not possible to directly measure the effect of vegetation-reduced wind speeds on storm surge heights because the effect would never occur independently of other effects, such as increased drag on the water flow from the vegetation, numerical models can be used to explore the likely effect of reduced wind speeds on peak water levels. Simulations of Hurricanes Betsy and Andrew found that peak water levels were more than one meter lower in some areas when wind speeds were modified to reflect likely reductions caused by vegetation (marshes and wetland forests in this case, rather than mangroves; Westerink et al. 2008). This implies that the effects of vegetation on wind speeds could significantly influence storm-surge water levels.

Reduced damage and loss of life behind mangroves

A small number of studies have investigated whether mangroves help to reduce damage and loss of life during storm surges. Based on a study of three villages in Orissa, India, following the Odisha cyclone in October 1999, Badola and Hussain (2005) found that in the mangrove-protected village, damage to houses and other adverse effects were lowest compared to the other two villages, while crop yields and other positive factors were least impacted. The loss incurred per household was highest in the village that was protected by an embankment ($153.74), followed by the village with no protection ($44.02), with the lowest losses in the village protected by mangroves ($33.31). The reason losses were so high in the embankment-surrounded village was that the embankments were breached. This allowed in sea water, but subsequently the sea water took time to drain out of the breaches, so that crops were damaged more than in the village with no protection that suffered the highest level of inundation, but which drained quickly. Badola and Hussain (2005) note that embankments near the mangrove forest were not breached while those further away were breached in a number of places, suggesting that mangroves may have helped to protect those embankments.

Based on a larger-scale study using data from over 400 villages after the same cyclone and in the same region, Das and Vincent (2009) found that villages with wider coastal mangrove belts had significantly fewer deaths than villages with narrower mangrove belts or no mangroves (in 1949 mangroves had fronted all the villages). Using a statistical model (Table 2.2), Das and Vincent predicted that there would have been 1.72 additional deaths per village within 10 kilometers of the coast, if mangroves had not been present. They pointed out that mangroves saved fewer lives than an early warning issued by the government, which saved 5.84 lives per village. However, for those people who stayed behind despite the warning, the mangroves reduced the number of deaths (Vincent and Das 2009; see also Baird et al. 2009, for further discussion of these results). This study demonstrates how a combination of different risk reduction measures (in this case, early warning systems and mangrove forests) provided an increased level of protection in comparison to either measure alone.

It should be noted that the above comparisons between villages assume that the characteristics of the cyclone-generated waves and water levels were similar at the different locations with and without mangroves. This is not always the case as wave heights and water levels may vary over short distances. However, in the study by Das and Vincent (2009), this is unlikely to be an issue because of the large number of villages included in the analysis, their relative proximity along the same stretch of coast, and the inclusion of such factors as distance from coast in their statistical model.

Mangroves can also help people recover after coastal disasters by providing firewood, building materials, and food sources (for example, fish and shellfish that live among mangrove aerial roots).

The effect of tropical cyclones and storm surges on mangroves

While mangroves can reduce storm-surge peak water levels, they can also be affected by cyclones and their accompanying storm surges. Smaller cyclones and storm surges may result in some tree mortality and defoliation, but in most cases the structural complexity of the forest is maintained, and the forest is able to recover. During extreme events, tree mortality can be more extensive, caused by the breaking of trunks, uprooting of trees, the loosening or shredding of bark, and severe defoliation (Jimenez et al. 1985; McCoy et al. 1996; Lacambra et al. 2008; Tanaka 2008). The flooding and siltation that may accompany cyclones can cause further tree mortality (Jimenez et al. 1985; Lacambra et al. 2008). If mass tree mortality occurs, it may result in the subsequent collapse of sediment and loss of surface elevation, as dead roots decay, and in some cases this can prevent recolonization for some years (Cahoon 2006).

The force of the water currents within the storm surge, the waves riding on the storm surge, and the high winds can cause tree damage. Larger trees are more likely to be damaged, and some species of mangroves may fare better than others. For example, after Hurricane Andrew passed across Florida in 1992, *Rhizophora mangle* fared better than *Avicennia germinans,* and both fared better than *Laguncularia racemosa* (McCoy et al. 1996).

While cyclones can alter the structure of mangrove vegetation, in many areas such cyclones are infrequent and mangrove forests are usually able to recover their structural integrity over a number of decades, before another cyclone affects the same area (Krauss et al. 2009). The speed of recovery after events is likely to be determined by the magnitude of the event and local conditions. This makes it difficult to predict the long-term effects of cyclones and storm surges on mangroves in any particular location.

The use of mangroves in risk reduction from cyclone impacts

By reducing wave height and storm surge depth, mangroves can reduce flood risk from cyclones to coastal communities and properties. In practice, where human resources are in close proximity to mangrove coastlines, mangroves are best seen as part of a wider risk reduction strategy, which may also include measures such as sea walls, dykes or levees, and early warning systems, evacuation plans, and refuges. A number of places, such as the Philippines and Vietnam, have used mangrove restoration extensively for risk reduction (see discussion of these cases in Section 6). A nonrestoration example of how mangroves can provide coastal defense services comes from Cairns, Australia, which was affected by Cyclone Larry in 2006. Using an early warning system and following detailed evacuation plans and procedures, the various commercial, recreational, and naval vessels that were present in Cairns Port moved deep into the mangrove creeks to wait out the storm (Williams et al. 2007). All vessels rode out the storm safely with no loss of life. The combination of an early warning system, evacuation plans, and the presence of mangrove forests all contributed to this positive outcome.

Summary: Storm Surge

Both empirical data and numerical models suggest that mangroves can play a role in reducing storm-surge peak water levels, when the mangroves are present over sufficiently large areas. Studies measured reductions in peak water levels of four to 48 centimeters per kilometer of mangrove. In low-lying areas, even relatively small reductions in peak water levels could reduce flood extent and damage to property.

The relationship between storm surge reduction, bathymetry, topography, distance from shore, and width of mangrove vegetation is highly complex; numerical models based on the underlying physics of wind forcing and water movement are best able to represent the behavior of storm surges (Resio and Westerink 2008). Such models are needed to explore the effects of different factors on storm-surge reduction rates through mangroves. The simulations by Zhang et al. (2012) demonstrated that peak water levels are expected to decline non-linearly with distance, with the greatest reduction in peak water level per unit distance occurring at the seaward margin.

The ability of mangroves to reduce storm surges also depends on the storm surge forward speed, the height of the storm surge, and the cyclone intensity. Numerical models suggest that mangroves will be more efficient at reducing surge height for fast-moving surges. Extreme events, with very strong winds or surges many meters high, may damage or destroy mangroves, limiting their ability to reduce surge height. The threshold at which such damage occurs is likely to depend on mangrove species and height. Such damage is usually localized to areas that are relatively close to the storm track.

To date, numerical models have not included spatial variation in mangrove characteristics, such as mangrove density. It is very likely that sparse, fragmented, or channelized areas will be less effective at reducing storm surge water levels than dense mangrove vegetation.

2.5| Tsunamis

There is still debate about the role that mangroves play during tsunamis in reducing loss of life and damage to property. Evidence comes from two types of studies: the use of physical or numerical models to estimate reductions in tsunami height, flow speed, or other tsunami characteristics behind coastal vegetation; and direct observations of casualties or damage behind vegetation following tsunamis, such as the Great Asian Tsunami of 2004. The following reviews these two types of evidence in turn.

Modeling tsunamis flowing through mangroves

A number of modeling studies have focused on the capacity of mangroves or coastal forests to reduce the force, velocity, or height of a tsunami. The following draws on a selection of these studies, which focus on the physical changes in tsunami characteristics when a tsunami enters a mangrove forest or other type of coastal forest. These studies suggest that mangroves and coastal forests can play a role in reducing tsunami flood characteristics, as shown in Table 2.3.

These studies are based either on physical models or numerical models, some of which were validated using data collected after the 2004 tsunami. The studies mostly considered mangrove belts between 100 and 500 meters wide. They examined a variety of tsunami characteristics, including flood depth, current velocity, tsunami pressure, hydraulic force, run-up height/distance, and inundation extent. All of these were seen to be reduced behind vegetation in the studies shown in Table 2.3. While tsunami force was reduced by 70 percent in one model (Yaganisawa et al. 2010), the reduction in flood depth was more modest, in the region of 5 to 30 percent (based on several different models, as shown in Table 2.3).

In front of vegetation (that is, seaward of vegetation), some tsunami characteristics were increased, such as water level and water pressure. The forests obstruct the flow, causing some water to back up in front of the vegetation. However, mangroves are only able to reduce these tsunami characteristics within certain limits, relating to the ability of trees to withstand the force of the tsunami. Yaganisawa et al. (2009, 2010) studied the fragility of mangroves in the face of different tsunami wave heights, and found that trees were destroyed by tsunamis greater than 3 to 4 meters in depth (discussed below).

As for all types of waves, the width of the mangrove forest affects the reduction of tsunami inundation depth, current velocity, and run-up distance (Harada and Imamura 2005, Table 2.3). Ohira et al. (2012) used the two-dimensional numerical model of Harada and Imamura (2005) to further explore the effect of forest width. With tsunami depth in front of the forest set to not exceed four meters (the tree fragility limit), they explored the capacity of 20, 40, 60, 80, 100, and 200-meter-wide forests, two kilometers in length, to reduce inundation depth, area, flux, and run-up distance. Their results are shown in Table 2.4. While the 20-meter-wide forest had little effect, the 200-meter-wide forest was able to reduce inundation depth, area, and run-up distance by approximately 10 percent. Ohira et al. found that exponential functions could be used to describe the relationship between forest width and tsunami inundation transmission.

Factors affecting mangrove capacity to reduce tsunamis

Alongi (2008) considers that the following factors are likely to be important in determining the extent of protection that mangroves can provide from tsunamis: width of forest, slope of forest floor, tree density, tree diameter, proportion of above-ground biomass vested in roots, tree height, soil texture, forest location (open coast versus lagoon), type of adjacent lowland vegetation and cover, presence of foreshore habitats (sea grass meadows, coral reefs, and dunes), size and speed of tsunami, distance from tectonic event, and angle of tsunami incursion relative to the coastline. These factors can be broadly divided into (i) tsunami characteristics at the point of entry into the mangrove forest, and (ii) mangrove characteristics. The following sections discuss this in more detail.

Tsunami characteristics: Key aspects of a tsunami that affect the capacity of mangroves to reduce its effects include whether it is a breaking wave versus a nonbreaking wave (which is likely to be affected by local bathymetry), and the height of the wave as it comes on shore, which determines whether the mangroves themselves will be destroyed by it.

Table 2.3: The Effect of Mangroves or Coastal Forests on Tsunamis

Type of study and source	Location	Vegetation type	Tsunami reduction information
Physical scale models			
Hydraulic experiments using five kinds of physical model including ones to represent mangroves and coastal forest (Harada and Imamura, 2001)		Mangroves represented by barriers consisting of pillars and porous sheets to represent aerial roots, trunks and leaves at different heights above the ground.	Water height, current velocity and pressure were reduced behind all permeable structures tested (including the model mangrove) as compared to the case without the permeable structure. The hydraulic force was reduced behind the permeable structures, and this resulted partically from reflection of the tsunami wave back out to sea and partially because of energy dissipation as the water flowed through the model forest.
Wave channel experiment (Hiraishi and Harada, 2003)		Porous media used to model leaves and aerial roots; plastic columns used for tree trunks.	Water level and current velocity were lower behind model compared to the case where the model forest was not present. Water levels increased in front of the model due to wave reflection. Tsunami pressure was increased in front of the model (compared to the case with no model), but was reduced at a point behind the model.
Laboratory scale model of sandy beach with coastal forest (Irtem et al., 2009)		Coastal forest constructed using artificial trees and cylindrical wooden sticks.	Run-up height was reduced by up to 45% by the model forest, compared to no trees/sticks being present, with variation depending on geometrical arrangement of model trees.
Numerical models and simulations			
2-dimensional numerical model using the momentum equation, and Morison's equation to include the hydraulic resistance force from the coastal forest (Harada and Imamura, 2005)	Sendai Bay, Japan	Pine trees modelled at different densities and different widths	Models show that coastal forest increases the reflection of the tsunami wave, reducing inundation depth and run-up distance. Wider forests reduced inundation depths, current velocity and hydraulic force.
Simulation using model (Delft3D-FLOW), validated using field data (Gelfenbaum et al., 2007)	Kuala Meurisi, 100km south of Banda Aceh, Sumatra, Indonesia	Mangroves modeled as a group of parallel, staggered or randomly arrange rigid vertical cylinders	Mangrove forests reduced the water levels and flow speeds reached during tsunami inundation. The maximum water level reached at a location approximately 200 m landward of the mangrove forest was 80–91% of the maximum water level with no mangrove forest.The presence of mangroves also resulted in sedimentation in the mangrove zone, compared with erosion in the absence of mangroves.

(*continued on next page*)

Table 2.3: The Effect of Mangroves or Coastal Forests on Tsunamis *(continued)*

Type of study and source	Location	Vegetation type	Tsunami reduction information
2-dimensional depth-integrated numerical model (Teo et al., 2009)	Merbok estuary, Kedah, Malaysia	Trees modelled as circular cylinders	When trees were included in the model, tsunami water levels were reduced at the head of the estuary (compared to trees absent). Water levels downstream of the mangrove area were higher (compared to trees absent), due to the blockage created by the mangroves.
Field surveys and numerical analysis, including modelling fragility function of mangroves to tsunami height (Yaganisawa et al., 2009)	Pakarang Cape, Pang Nga Province, Thailand	Mangroves assumed to be *Rhizophora sp.*, density 0.2 trees/m^2, stem diameter 15cm, in a 400m wide area	Using a model that included a fragility function of mangroves based on stem diameter and tsunami height, mangrove forests can reduce tsunami inundation depth by 30% for a 3.0m inundation depth and 30 min wave period. When the tsunami inundation depth exceeded 3m, the reduction effect was reduced due to the tsunami destroying the mangrove forest (50% destroyed by 4.5 m tsunami inundation depth, most destoryed by 6 m tsunami).
Model based on leapfrog finite different method of nonlinear shallow water wave equation (Yaganisawa et al., 2010, using model from Yaganisawa et al., 2009)	Banda Aceh, Indonesia	Mangroves included as a variable roughness coefficient estimated by a roughness model based on the occupancy ratio of trees in a control volume/area	Model suggests that a 10 year old mangrove forest in a 500 m wide belt could reduce tsunami hydrodynamic force by approximately 70% for an incident wave of 3.0 m inundation depth with a wave period of 40 minutes at the shoreline. When tsunami inundation depth exceeded 4 m, the forest was mostly destroyed.
ComMIT and Mike 21 FM models used to hindcast observed tsunami inundation (Kaiser et al., 2011)	Andaman Sea coast, Thailand	Vegetation included using Manning's n (a roughness coefficient) based on field measurements and land cover maps.	Topography is the most critical factor influencing inundation patterns. Dense vegetation strongly influenced flow velocities; these were reduced up to 50% by mangroves. Inundation extent was influenced to a smaller extent by vegetation. Water levels increased in the area in front of (seaward of) mangroves, but were lower in the area behind (landwards of) mangroves.
2-dimensional numerical model (Ohira et al., 2012, using model of Harada and Imamuma, 2005)	Yogyakarta, Indonesia	Forest characteristics in model based on *Casuarina* plantation, 4 trees/100m^2, DBH 0.20m. Different forest widths tested.	With a 100m wide, 2km long forest, on a representative topography, the forest reduced inunation flux by 17.6%, flood depth by 7.0% and flood area by 5.7%. Using actual topogography for 100m width forest along 2.46km^2, expected reduction in inundation flux was 10.1%.

Table 2.4: Change in Tsunami Inundation Flux, Depth, Area, and Run-up Distance as the Tsunami Passed through Different width Forests (data from numerical simulations conducted by Ohira et al. 2012)

Forest	Inundation flux				Inunation area		Run-up distance	
width (m)	m2/s	transmission %	m	transmission %	km2	transmission %	km	transmission %
20	5.89	90.9	1.81	96.8	5.35	98.5	2.60	97.0
40	5.67	87.5	1.76	94.1	5.28	97.2	2.57	95.9
60	5.58	86.1	1.76	94.1	5.21	95.9	2.54	94.8
80	5.42	83.6	1.75	93.6	5.16	95.0	2.52	94.0
100	5.34	82.4	1.74	93.0	5.12	94.3	2.48	92.5
200	4.87	75.2	1.73	92.5	4.90	90.2	2.36	88.1

Mangroves are more able to absorb the energy of breaking waves as opposed to nonbreaking waves. Husrin et al. (2012) and Strusińska-Correia et al. (2013) found that the highest wave reduction occurred with breaking waves over the widest forest, based on a physical model of a tsunami entering a forest. The model forest performed poorly against nonbreaking tsunami waves. Apotsos et al. (2011) also found that increased surface roughness (such as that caused by forest cover) reduced the maximum run-up elevation and maximum wave velocity for breaking and near-breaking waves, while less effect was seen for nonbreaking waves.

Tsunami wave period is also important. Even with a wide forest belt, tsunamis with longer period waves resulted in greater inundation depths and greater hydraulic forces, based on the model of Harada and Imamura (2005). Variation in the response of tsunami characteristics to mangroves may also occur between the different waves that make up a tsunami wave train (Gelfenbaum et al. 2007).

Vegetation characteristics: Forest density is expected to affect tsunami flows. Simulations using the Delft3D-FLOW model (validated using field data from the 2004 tsunami in Aceh; Table 2.3) found that increased mangrove densities decreased the maximum water level, run-up height, and maximum flow speed (Gelfenbaum et al. 2007, Table 2.3). However, Harada and Imamura (2005) found that forest density had less influence on inundation depths, currents, and hydraulic force than forest width (based on a two-dimensional numerical model of a three meter tsunami passing through a 50-meter-wide forest with either 10, 30, or 50 trees per 100 m^2).

Other vegetation measures that influence tsunami characteristics include the submerged tree volume (that is, the volume of vegetation that is under water) and the tree's frontal area (this is the same as the projected area, described above). Husrin et al. (2012) found that these measures influenced the hydraulic resistance to tsunami flow provided by trees, based on their physical model of tsunami flows.

The combination of tsunami and mangrove characteristics, which affects tree breaking: Tsunami height (related to hydraulic force) is important, because large tsunamis can damage or break trees. As long as trees are able to withstand the tsunami force, they not only reduce tsunami flow, but can also trap debris, which would otherwise increase the destructive force of the tsunami. However, once they are broken, the trees contribute to this floating debris.

Yaganisawa et al. (2009) modeled the effect of tree breakage and included a mangrove fragility function based on stem diameter and tsunami height. They found that mangrove forests could reduce tsunami inundation depth by 30 percent for a three-meter inundation depth and 30-minute wave period. When the tsunami inundation depth exceeded three meters, the reduction effect was reduced due to the tsunami destroying the mangrove forest. A 4.5-meter tsunami inundation depth destroyed 50 percent of the mangrove forest, and most of the forest when the depth reached 6 meters. In a separate study, Yaganisawa et al. (2010) again found that for tsunami inundation depths greater than four meters, the forest would mostly be destroyed and therefore would not reduce the hydrodynamic force of the tsunami.

Tanaka et al. (2007) found that when the main trunks of coastal trees (several species) had a diameter greater than 10 centimeters, they were seldom broken by tsunamis. However, there were exceptions to this: the trunks of *Rhizophora apiculata* were broken on Kang Island, Thailand, under the force of an eight-meter tsunami wave, and the trunks of *Rhizophora mucronata* were broken on Medilla, Sri Lanka with a six-meter tsunami (based on observations of tsunami damage to trees following the 2004 tsunami). Tanaka et al. (2007) note that the aerial roots of *Rhizophora* spp. trees allowed the moment of the drag force to be shared between them, so that they were able to withstand a five-meter tsunami. When the drag moment exceeds the threshold for the breaking moment, the trunks of these species were broken just above the aerial roots.

Tsunamis can uproot trees. Tanaka et al. (2007) noted that uprooting usually occurred at the front of the vegetation, where roots were undercut by erosion. Most of the broken and uprooted trees were not washed away but remained where they had been growing. Inside coastal forests, erosion seldom occurred except for local scour around tree trunks, and this was not sufficient by itself to uproot trees.

Loss and damage studies

Following the Great Asian Tsunami in 2004, several studies and reviews explored whether mangroves reduced loss and damage in areas behind them (for example, Kathiresan and Rajendran 2005; Danielsen et al. 2005; Dahdouh-Guebas et al. 2005; Dahdouh-Guebas and Koedam 2006; Danielsen et al. 2006; Olwig et al. 2007; Forbes and Broadhead 2007; Iverson and Prasad 2007; Alongi 2008; Baird and Kerr 2008; Iverson and Prasad 2008; Mukherjee et al. 2008; Cochard et al. 2008; Lacambra et al. 2008; Kerr et al. 2009; Rasmussen et al. 2009; Tanaka 2009; Cochard 2011). Many of the studies were disputed, and there was considerable debate about the validity of the data or approaches used. However, it is beyond the scope of this report to examine these studies or their critiques further.

Laso-Bayas et al. (2011) led a study for which there has so far been little debate. They used a spatial statistical analysis (a spatial generalized linear mixed model) to estimate the effect of coastal vegetation on tsunami damage and casualties in an area of Aceh, using field data and remote-sensing (satellite) data. The vegetation in the study area did not include mangroves, but did include coastal vegetation, in the form of plantations of coconut and rubber trees. Laso-Bayas et al. (2011) found that distance from the coast was the dominant determinant of tsunami impacts, measured as number of casualties and structural damage. Additionally, they found that the presence of vegetation in front of settlements (represented in their model as an increase in land cover roughness) reduced the number of casualties by an average of five percent. However, dense vegetation behind settlements increased the amount of structural damage that occurred.

Summary: Tsunamis

Several physical and numerical modeling studies suggest that mangroves can reduce tsunami flood depth, current velocity, tsunami pressure, hydraulic force, run-up height/distance, and inundation extent. Flood depth is expected to be reduced by 5 to 30 percent by mangrove belts that are several hundred meters wide. As well as mangrove width, other key factors influencing the rate of reduction of tsunami characteristics include vegetation density, whether the tsunami is a breaking or nonbreaking wave, and wave period.

Tsunamis above approximately four meters in height are likely to destroy mangroves, rendering them ineffective at reducing tsunamis. Once trees have been broken by the flow of water, they will contribute to the debris carried by the tsunami flow, potentially causing more damage further inland.

Tsunami water levels may be increased in front of (that is, seaward of) vegetated areas, potentially resulting in further loss and damage in these areas.

2.6| Mangroves as a Form of Sustainable Coastal Defense

The continued provision of mangrove coastal defense services depends on their capacity to adapt to future changes, in particular to projected rates of sea-level rise. In some areas, mangroves may be able to keep pace with rising sea levels through an increase in the height of their soil surface elevation (Figure 2.8).

Historically, some mangrove areas have kept pace with sea level rise over thousands of years; an example of this can be seen at Twin Cays, Belize (McKee et al. 2007; Figure 2.9). Studies of soil cores suggest that soils built up at rates of one millimeter/year to 10 millimeters/year in different locations and settings (reviewed in Ellison, 2009). However, in other areas, mangroves were not able to keep up with rates of sea level rise, and were drowned by rising sea levels. This shows that while mangroves can sometimes keep pace with sea-level rise, this depends on various other factors and the local rate of sea-level rise.

Recent evidence of soil elevation change (based on measurements using the Surface-Elevation Table – Marker Horizon methodology, from studies published between 2006 and 2011) suggest that mangrove surfaces are rising at similar rates to sea level in a number of locations (Table 2.5; reviewed in McIvor et al. 2013). However, these measurements are from a relatively small number of sites, and most records span short time periods.

Figure 2.8: Diagram Showing how Mangrove Soil Surfaces can Rise with Sea-level Rise, Potentially Allowing Mangroves to Keep Pace with Sea-level Rise

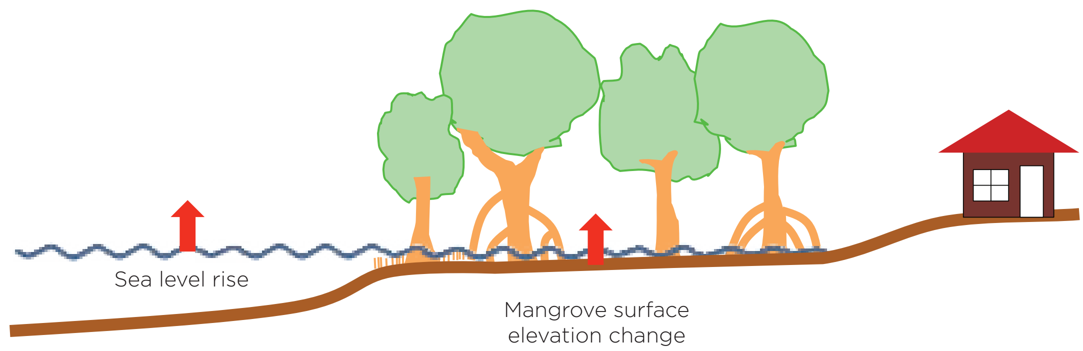


Figure 2.9: Graph Showing that Mangroves in Belize Have Accumulated Peat at a Rate Consistent with Sea-level Rise in the Caribbean area (data from Toscano and Macintyre 2003 [sea-level curve] and McKee et al. 2007 [mangrove peat data])

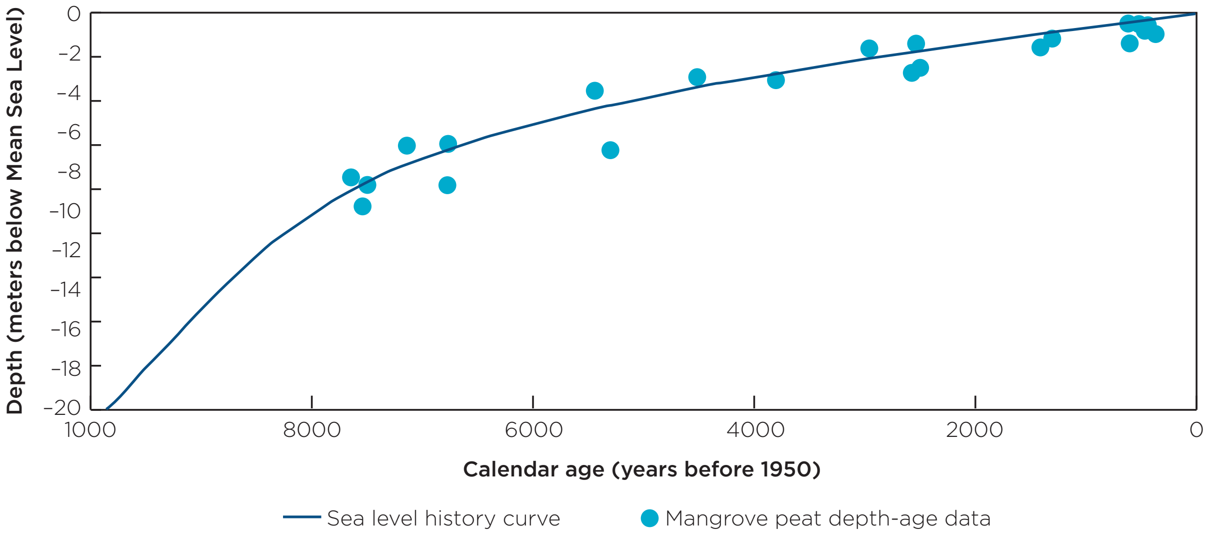


Table 2.5: Mangrove Locations with Measures of Surface Elevation Change and Rates of Relative Sea-level Rise

Location	Surface elevation change (mm/yr)	Record length (years)	Relative sea level rise rate (mm/yr)	Source
Rookery Bay and Naples Bay, Florida, United States	+0.61 to +3.85	3	2.1	McKee 2011
Twin Cays, Belize	-3.7 to +4.1	3.5	2.0	McKee et al. 2007; McKee 2011
Various sites on Kosrae and Pohnpei, Micronesia	-5.8 to +6.3	1.4 or 3	1.8	Krauss et al. 2010
Moreton Bay, Australia	+1.4 to +5.9	3	2.4	Lovelock et al. 2011
Several sites in Australia	-2.6 to +5.64	3	-0.5 to +4.1	Rogers et al. 2006

Several processes are known to influence surface elevation change in mangroves, including sedimentation, accretion, erosion, growth of subsurface roots, and the compaction of soils over time. Factors that affect these processes and, therefore, the rate of surface elevation change, include the supply of external sediment, vegetation characteristics, such as tree density and aerial root structure, nutrient availability to subsurface roots, storm impacts, and several hydrological factors, such as river levels, rainfall, and groundwater pressure.

Threshold rates of sea-level rise are likely to exist, beyond which mangrove surface elevation changes are no longer able to keep up. These thresholds are likely to vary in different locations (for example, depending on local rates of sediment supply). Because of the large number of processes and factors involved, prediction of future surface-elevation change is very challenging. McIvor et al. (2013) review these topics in more depth.

In conclusion, it is likely that many mangrove areas may be able to keep pace with moderate rates of sea level rise, provided the areas are managed wisely (for example, by maintaining sediment inputs, protecting mangroves from degradation). However, it would also be prudent to ensure that space is left behind current mangrove areas to allow them to colonize these areas as sea level rises. Actions that contribute to mangrove survival with sea-level rise will help to maintain the coastal defense functions of mangroves into the future. Currently, short-term anthropogenic losses of mangroves represent a greater threat to their provision of coastal defense services than the long-term effects of sea-level rise.

2.7| Conclusions

Mangroves can contribute to the reduction of coastal hazards, including wind and swell waves, storm surges, and tsunamis. As such, they are able to reduce loss and damage from these hazards, with associated reductions in economic losses. Therefore, the appropriate management and conservation of mangroves has value, and accounting for this value is needed in order to enable the best decisions to be made along stretches of coast that are both subject to these hazards and have mangrove vegetation.

It is important to note that hazards are usually only partially reduced by mangroves. However, even small changes in water levels can result in reduced flood extents and, therefore, reduced damage to property and loss of life. It is rarely appropriate for mangroves to provide the only form of coastal defense. Mangroves can contribute to coastal risk reduction strategies alongside other risk reduction measures, such as structural defenses, early warning systems, or planning approaches that ensure that dwellings are not placed in high-risk zones.

The capacity of mangroves to reduce hazards may be limited by characteristics of the hazard, such as tsunami height or wind speeds during cyclones, which can also destroy mangroves. This also needs to be taken into account when planning coastal risk-reduction strategies, and is a further reason for ensuring a diverse approach to risk reduction.

While a number of factors are likely to affect the ability of mangrove to reduce these coastal hazards, the most important factor is mangrove forest width. Generally, a mangrove belt several hundred meters wide is desirable. Dense forests are expected to be most effective at reducing hazards, and mangrove species with aerial roots are better able to reduce wind and swell waves and also to withstand inundation by tsunamis. However, in terms of coastal planning, risk reduction strategies need to be designed on a case-by-case basis, taking into account the local hazard context, local geomorphology and bathymetry, local mangrove characteristics, and the population needing protection.

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3| Coastal Defense Services Provided by Coral Reefs

Philip A. Kramer
The Nature Conservancy

3.1| Summary

Coral reefs are among the most biologically diverse and economically valuable ecosystems. Of particular value is the role coral reefs provide in protecting coastal communities from natural hazards, such as flooding, coastal storms, and sea-level rise. Coral reefs naturally protect coasts from erosion and flooding by absorbing wave energy, as well as supplying and trapping sediment found on adjacent beaches. Coral reefs reduce wave energy by up to 97 percent (Ferrario et al. 2014). Reefs function similar to low-crested breakwaters whose hydrodynamic behavior is well characterized by coastal engineering models and field demonstrations (Sheppard et al. 2005; Gallop et al. 2014). 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. Unlike artificial breakwaters that require significant maintenance costs, coral reefs are self-sustaining as long as they remain healthy. Healthy reefs can provide a significant part of coastal protection even during cyclones under strong wave conditions (Blanchon et al. 2010). However, declines in the condition of coral reefs in places (for example, Great Barrier Reef, see De'ath et al. 2012; or the Caribbean, see Jackson et al. 2014) coupled with increasing rates of global sea-level rise are jeopardizing communities and coastal infrastructure, particularly in low-lying small island developing states. Further, the potential impacts of climate change, including sea-level rise and coral mortality under warmer and more acidic waters (IPCC 2014), may reduce the protection they offer (Baldock et al. 2014; Hoegh-Guldberg et al. 2011).

Reducing threats to coral reefs, such as overfishing and poor water quality, and establishing marine reserves, can all directly benefit reefs and maintain their shoreline protection services. Degraded reefs can be structurally and functionally restored using biological, physical, and artificial techniques. Reef restoration has been shown to be cost effective in comparison to the development of traditional submerged breakwaters (Fabian et al. 2014; Ferrario et al. 2014; CCRIF 2010). Incorporating nature-based principles (for example, the biomorphology and geohydrology of the existing reef, existing and potential natural values, and drawing on materials and forces already present on the reef) into the design of engineered breakwater structures can yield a greater array of benefits (Waterman 2008). Restoration projects also benefit if local communities and cultural values are incorporated into design principles. Merging both ecological and engineering schools of thought into more mixed integrated designs may also be more cost effective than traditional hard infrastructure solutions. Methods for valuing the coastal protection services of natural reefs compared to engineered structures continues to evolve and will improve decision making and management approaches in the coastal zone.

3.2| Coral Reefs: Basic Ecology and Biogeography

Coral reefs are underwater structures built by corals and other organisms, such as coralline red algae that secrete calcium carbonate. They contain about 25 percent of the oceans biodiversity and are vitally important as a source of food, shelter, medicine, and cultural and aesthetic value to coastal communities. The characteristic of coral reefs is to grow vertically through the deposition of aragonite and other biogenic minerals, a feature that distinguishes them from ahermatypic reefs (nonreef building). Coral reefs occur to depths of about 50 meters with the majority of coral growth often found at 10 to 20 m. Although there are hermatypic deep water coral reefs (greater than 50 meters) found in all the ocean basins, even into the polar regions, little is known about them and they do not play a significant shoreline protection service due to their great depths. Shallow water hermatypic coral reefs cover approximately 285, 000 square kilometers or 0.1 percent of the world's oceans. They occur most abundantly in clear shallow tropical waters on the windward sides of continents and islands. The Pacific Ocean and Southeast Asia each contain about one quarter of the world's coral reefs, followed by Australia (17 percent), the Indian Ocean (13 percent), the Atlantic (10 percent), and Middle East (6 percent). This review focuses on shallow coral reef barriers (water depths less than 5 meters) that play the largest role in wave attenuation and coastal defense.

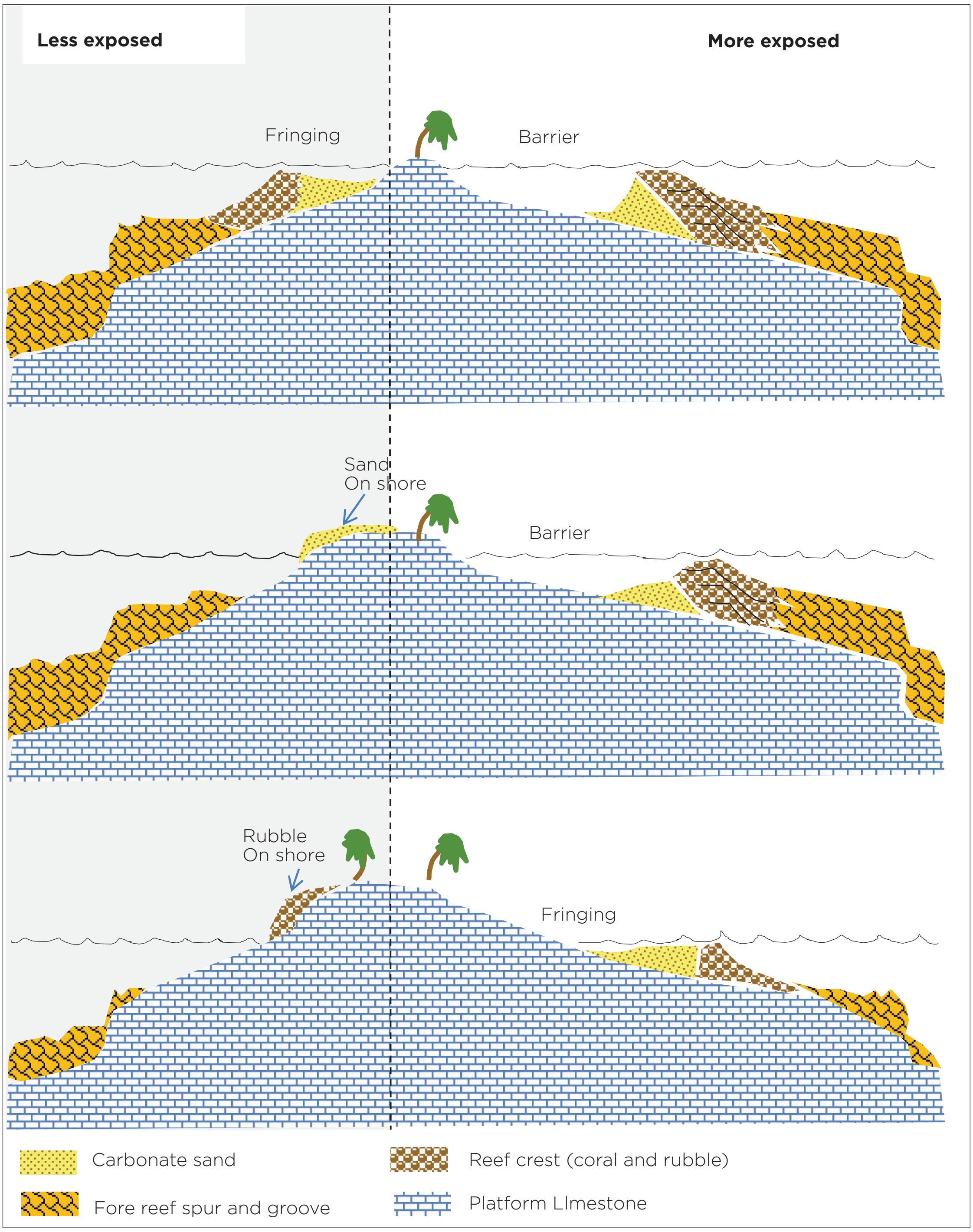
The process of carbonate production is an important aspect of the role reefs play in coastal defense and distinguishes them from other habitats, such as mangroves, which principally trap, rather than generate, sediment (Woodroffe 1992; Milliman 199.3). The balance between carbonate production and erosion over time controls the rate that reefs can grow vertically or accrete. Rates of carbonate production for coral reefs are some of the highest in the world and have been measured from 1000 to 4000 grams calcium carbonate per square meter per year (Mellela and Perry 2007 and reference within). Erosion works against carbonate production, causing a loss of the three-dimensional structural relief and a flattening of the reef surface over time. Erosion is mainly a function of bioerosion by fishes, echinoderms, and other bioeroding organisms, but reefs are also affected by physical and chemical erosion (Perry et al. 2013). 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 (Buddemier and Smith 1988). In a recent review of Caribbean reefs, Perry et al. (2013) found that today many shallow (less than 5 meters water depths) reefs in the Caribbean are accreting at much lower rates (about 0.68 millimeter per year) mainly because of recent losses in large reef-building acroporid corals. Under current rates of erosion, Caribbean reefs are thought to need at least 10 percent live coral cover to maintain their reef surface (Perry et al. 2013).

Shallow coral reefs can have distinctly different compositions, shapes, and zonation, all of which influence their wave-breaking characteristics and coastal protection properties. Three main types have long been distinguished (fringing, barrier, and atoll), but over a dozen geomorphic types have been described and mapped (Andrefouet et al. 2006). Most reefs contain predictable zones of coral development from offshore to inshore, including fore reef, reef crest, reef flat, and back reef zones. The location and morphology of these zones are the result of antecedent topography, as well as the interplay between coral growth and wave energy (Figure 3.1). The width of back reef lagoons can vary considerably from greater than 10 kilometers in the case of barrier reefs to being nonexistent in near shore fringing reefs. Water depths of back reef lagoons can exceed 30 meters in barrier reefs or where there is high sediment runoff from adjacent land masses.

3.3| Role of Coral Reefs in Coastal Protection

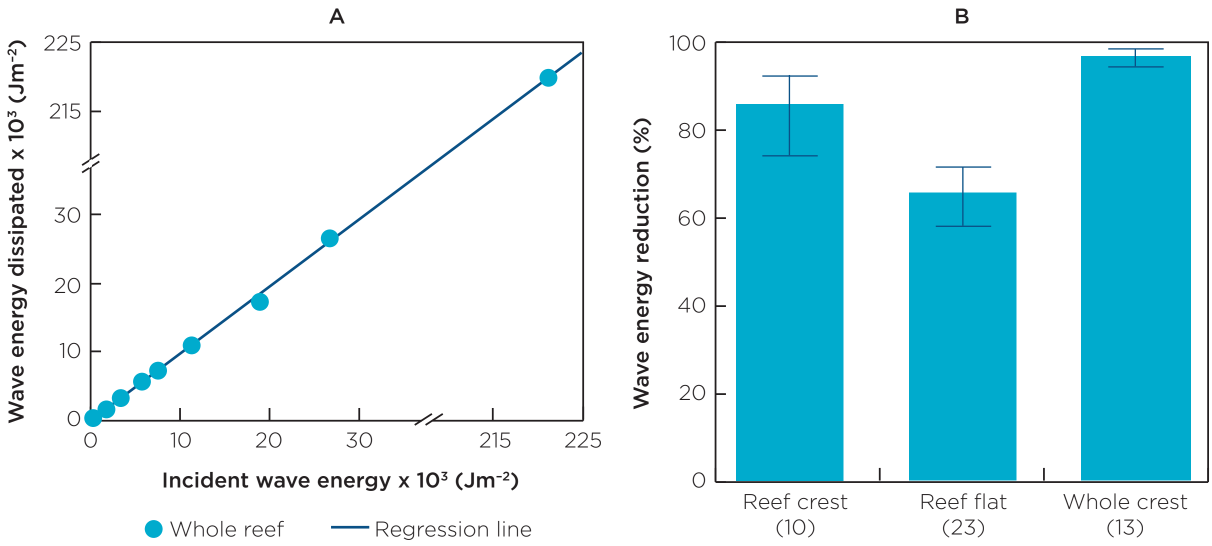
Coral reefs protect shorelines by absorbing and dispersing a significant part of the wave energy that otherwise would be transmitted onshore. This mainly occurs by breaking waves at the seaward edge of the reef and through bottom friction as the waves cross the reefs (Gourlay 1994, 1996a, b; Hardy and Young 1996; Wolanski 1994). After waves break and attenuate, the mean water level raises onshore (set-up) and currents and reef circulation are set in motion, mobilizing the transport of sediments, nutrients, and larvae (Longuet-Higgins and Stewart 1962; Symonds et al. 1995; Lowe et al. 2005). A substantial amount of wave energy dissipated from a wave as it passes across a reef.

Figure 3.1: Coral Reef Types and Morphology related to Exposure and Platform Slope and Width



Reef crests were found to dissipate 86 percent of the total incident wave energy, while reef flats dissipated 65 percent of the remaining wave energy (Ferrario et al. 2014). The whole reef (reef crest and reef flat) accounted for 97 percent of the total wave energy reduction (Figure 3.2). Appendix 3.1 provides an overview of the contributions of coral reefs to coast defense from 27 independent studies, including the Caribbean, Maldives, Australia, China, Japan, Guam, and Hawaii. Several

Figure 3.2: Wave Energy Reduction by Coral Reefs (adapted from Ferrario et al. 2014)

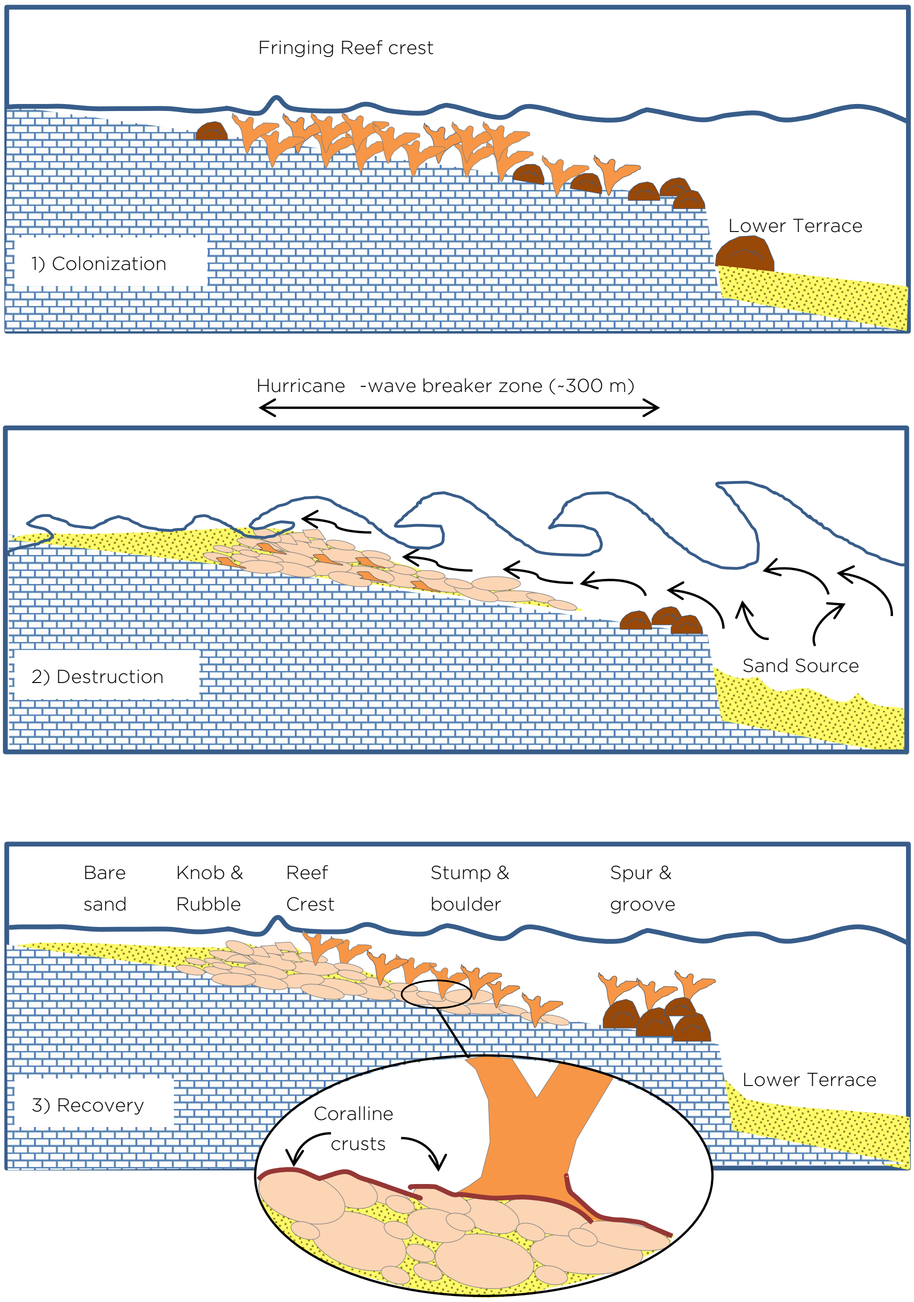


factors influence how effective coral reefs are in reducing wave energy and protecting coastlines, including water depth, reef morphology and slope, and reef surface roughness.

The depth of water above the reef surface is a critical factor in determining wave attenuation (Koch et al. 2009) and can vary by reef type, often depending on the degree of wave exposure and slope of the underlying platform (Gourlay 1996). Water depths are usually shallowest on the outermost reef crest or algal ridge (~ +/– 0.5 meters relative to MSL) where the majority of waves break over a distinct reef lip or edge. At low water, the greatest amount of the incident 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, wind waves) can pass across the reef crest onto the reef flat and back-reef areas (Brander et al. 2004; Lugo-Fernandez et al. 1998). Along with daily tides, water levels around reefs can have inter- and intra-annual variations, mainly associated with changes in atmospheric pressure and water temperature. In the spring, extreme low tides can occur, exposing reef crests for extended periods (Anthony and Kerswell 2013), whereas extreme high tides occur during the fall when cyclone activity is highest. During high-water cyclone events, such as Hurricane Wilma in the Yucatan, 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 Harday 1993). Very long period waves (for example, swell up to 30 meters generated from distant cyclones, tsunamis, and large tidal bores) can also raise water levels along the entire shelf, thereby allowing water to overtop reefs and be transmitted inshore. The extent of reef overtopping associated with these unusual and time-limited events (hours to a few days) will depend on their arrival time relative to daily tides (See Hoeke et al. 2013).

The morphology of the reef surfaces across the entire cross-shelf bathymetric profile also affects wave dispersion. This can include the shape and slope of the outer fore reef, dimensions of the outermost reef crest and reef flat (length, width), as well as the presence of back-reef coral and sand build-ups (for example, patch reefs and lagoonal sediment banks). The transmission of the wave energy from the offshore wave regime to the shoreline can vary greatly across reef geometries and properties (Rosman and Hench 2011; Baldock et al. 2014). Blanchon et al.

Figure 3.3: Full Cycle of Development of Fringing Reef Crest in a High Energy, Windward Setting



(2007) hypothesized that the morphology of shallow reefs is largely controlled by wave exposure and the underlying platform shelf width and slope (Figure 3.3). Steeper fore reef slopes (~>1:5) result in greater wave set-up (Gourlay 1996), but other factors, such as the frequency and depth of channels through the reef crest, can also influence wave breakage (Callaghan et al. 2006). The width of the reef crest and associated reef flat can range from a few meters to over several thousand meters. 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). Thus, even comparatively narrow reef flats dissipate much of the remaining wave energy. The total length and number of breaks (continuity) of reef surfaces also has an important effect on wave breaking and back-reef circulation dynamics. Breaks in the reef crest are fairly common and function as outlets for backreef waters that accumulate by across-the-reef wave-induced currents, wave set-up, and tides. Incident wave energy entering into the backreef decreases with the continuity of the reef crest. Indeed, the circulation across some atolls with continuous reef crests and only shallow channel breaks can be entirely driven by waves overtopping the windward side (such as wave pumping) (Callaghan et al. 2006). Discontinuous and semicontinuous reef crests in the Caribbean were found to reduce significantly less (about 27 percent) wave energy than continuous reef crests (Roberts 1980). However, some discontinuous reefs can cast a wave shadow much larger than the reef itself and in one case a matrix of isolated reefs was found to be remarkably effective at attenuating wave energy (Gallop et al. 2014).

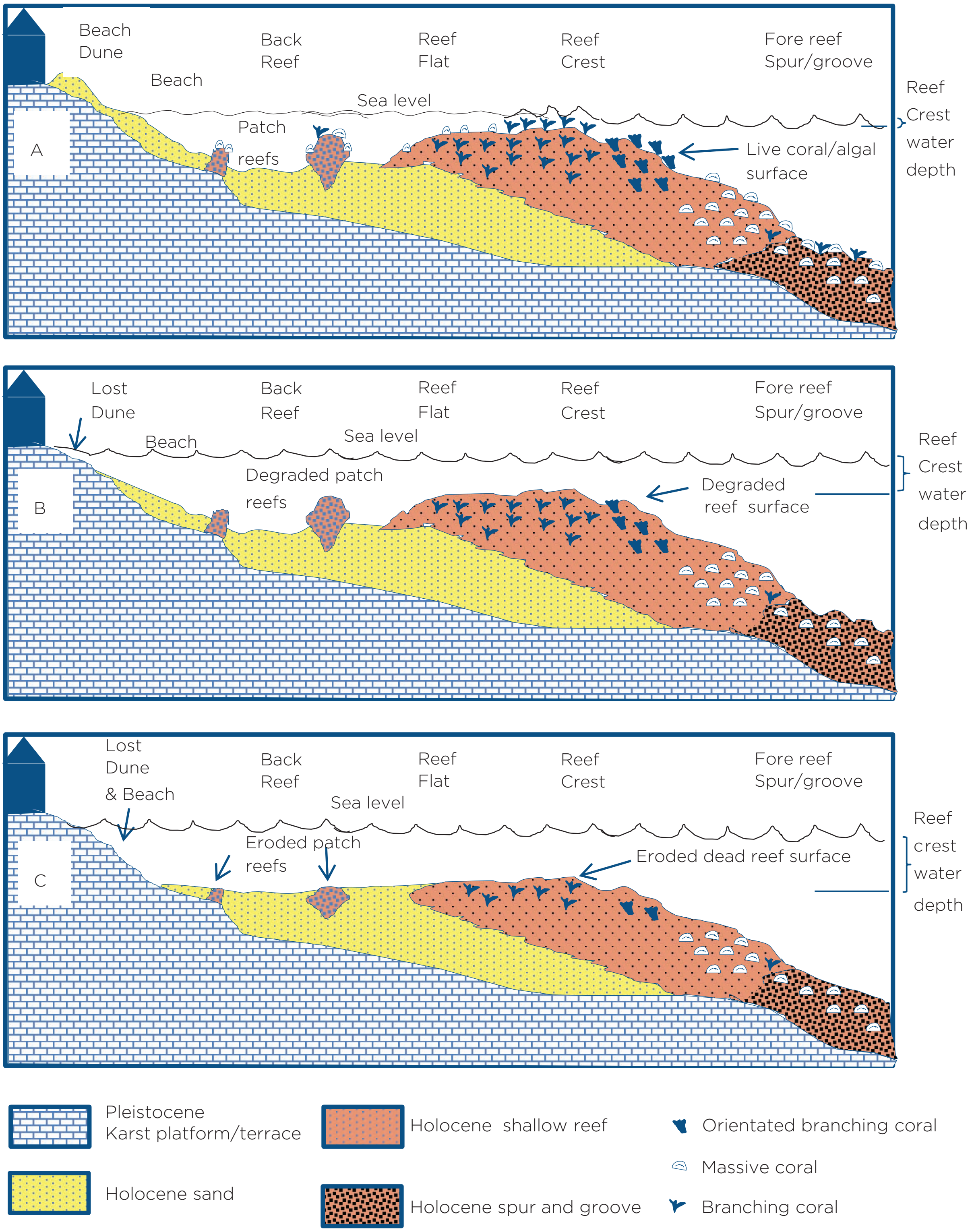
The reef rugosity, or surface roughness, is a third factor affecting wave attenuation. Surface roughness creates frictional and form drag (collectively referred to here as drag) as waves and currents passing over the reef. Rugosity is related to substrate type (Nelson 1996). Sand and pavement offer little friction; whereas large coral formations (greater than 30 centimeters) growing on the reef surface create the greatest friction and are the most important for wave attenuation. Drag over a reef flat may be about 10-times greater than drag over a sandy bottom, so coral structure at both the reef crest and across the reef flat plays an important role in attenuating wave energy (Lugo-Fernandez et al. 1998). The effect of drag on wave energy dissipation has been estimated to be substantial and increases as water levels over the reef crest decrease (Huang et al. 2012). When reef structural complexity is reduced due to storms or erosion, the ability to buffer wave energy is also decreased. The loss of reef rugosity can occur instantly in the case of direct physical damage (for example, storms or ship grounding) or more gradually following a mass coral mortality event (for example, mass bleaching followed by high coral mortality and unsuccessful coral recruitment). In low-lying areas, the loss of this function greatly increases the vulnerability of coastal areas to flooding (Figure 3.4). Sheppard et al. (2005) used Gourlay's model (1997) to determine changes in wave energy reaching the shoreline on 14 Seychelles fringing reefs from before the 1998 bleaching event to 2004, and projected for the next decade out. In their 2004 surveys, they found negligible recovery with greater than 99 percent of reef flat corals dead and a general rounding off of reef crest structure. Model results indicated greater wave energy and flooding of island beaches were correlated to the erosion potential (amount of three-dimensional structure that would be reduced by erosion). Assuming no coral recover, they predicted a doubling in the loss of coastal protection services over the decade following 2004.

In summary, a reef's cross-shore bathymetric profile, the height and width of the barrier (for example, reef crest), and surface rugosity are all important variables that influence the degree of wave attenuation. These parameters are well known from coastal engineering to be critical in estimating effects of structures on erosion and flood reduction. Indeed, there are many similarities between coral reefs and low-crested submerged breakwaters, which have been studied, modeled, and deployed extensively by coastal engineers (for example, Burcharth et al. 2007; Ranashinge and Turner 2006; Pilarczyk 2003). Much of this body of knowledge and experience can be applied to the design of reefs for coral reef and coastal restoration, including existing engineering tools and models.

3.4| Threats to Coral Reefs and Implications for Coastal Protection

Coastal defense functions of reefs will continue if reef accretion keeps pace with rising waters. For reef-building coral populations to persist, the rate of coral growth and recruitment must equal or exceed rates of mortality of adult corals. There is growing concern that coral mortality is increasing while coral recruitment, particularly for reef-building corals, is decreasing (Bruno and Selig 2007; Perry et al. 2013). Coral reefs are degraded worldwide (for example, Burke et al. 2011; Souter 2008; De´ath et al. 2012) because of overfishing, bleaching, biotic threats (such as crown-

Figure 3.4: Geological Units and Predicted Scenario of Wave Attenuation in Reefs under Different Management



of-thorns starfish outbreaks and disease), sedimentation and pollution, and destructive practices (such as coral mining and blast fishing). In the Caribbean, there has been a widespread loss of fast-growing, reef-building corals during the past 30 years (Jackson et al. 2014). Caribbean reefs today are increasingly dominated by small "weedy" corals that do not produce the carbonate volume necessary to maintain reef surfaces, much less keep up with rising sea levels (Perry et al. 2013). Less is known about the dynamics of crustose coralline algae, which play an important role in constructing shallow reef crests, because of the lack of research directed to these exposed higher energy reef crests.

The timescales for how changes in coral reef condition will influence whole-reef accretion dynamics and shoreline protection is not well understood because of high spatial and temporal variability in the erosion and deposition processes. There is some evidence to suggest that even in the face of accelerated sea-level rise, many coral reefs may remain viable protectors of shorelines for decades to come. For example, Webb and Kench (2010) studied the change in the sizes of 27 Pacific atolls and found that 86 percent remained stable or increased in size, even though sea level has increased at rates of about 2 millimeters per year. They suggested that erosion of reef islands is just one possible outcome, but concluded that reef islands are more geomorphologically enduring features than is often appreciated. Woodroffe (2008) also suggested that seaward shorelines of many atolls would continue to accrete, even with accelerated sea level rise, provided there is sufficient sediment supply from the growth and breakdown of the adjacent coral reefs. Indeed, even if reef growth declines and rates of erosion increase, some wave protection service will continue due to the inert limestone matrix underlying living reefs. However, wave protection services will eventually diminish over time, if reef health declines.

Net accretion of a reef ceases when rates of erosion exceed rates of growth and recruitment. The most immediate result is a flattening of the reef surface that reduces the height of the three-dimensional coral surface and the overall rugosity. As the reef surface flattens, water depths over the reef increase (Alvarez-Filip et al. 2009). The loss in rugosity decreases the drag on waves (see previous section). More wave energy begins to pass through the reef, resulting in increased wave orbital sizes in the back reef and potential secondary affects to inshore sea grass habitats (Saunders et al. 2014). Rates of erosion may also decrease as the loss of structural habitat, coupled with higher wave energy, makes reef crest habitats less attractive to parrotfish and other bioeroders. Reef areas that will be more susceptible to flattening include poorly managed reefs and those with fewer species of reef building coral (for example, biogeographic regions further away from such biodiversity hotspots as the Coral Triangle) or those near the environmental limits of coral growth (for example, cooler water temperature and lower visibility).

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. Marine protected areas (MPAs) can be an effective way to reduce threats to coral reefs and have been shown to enhance their recovery following disturbances (Mumby and Harbourne 2010). Marine reserves are now estimated to encompass nearly 10 percent of the world's reefs (Burke et al. 2011), although this amount is considered insufficient to ensure the protection of global coral reef diversity (Mora et al. 2006). An additional concern is the level of adequate management. Implementation varies considerably among MPAs and many MPAs remain "paper parks." Despite this, there is a trend of increased management effectiveness and improved financing to support enforcement and regulate human activities that are detrimental to reefs. Coastal communities are also being engaged in the management process through the use of locally managed access areas and Territorial Use Rights Fisheries (TURFS). However, destructive overfishing on coral reefs remains a significant problem, particularly where populations are high and reefs are a primary food source. Treating sewage and controlling runoff is also challenging in small-island developing states where local economies and decentralized development make advanced waste-water treatment challenging. 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.

3.5| Coral Reef Restoration

As human impacts to coral reefs have become more widespread and prevalent, so too have proactive actions to repair or replace disturbed or damaged reefs to return them to their previous state or, in other cases, to enhance them. Coral restoration has recently become a growing field of active research and experimentation that is beginning to offer a significantly wider array of actions for managers and policy makers to consider. These include both passive threat-reduction measures, such as eliminating the use of habitat-damaging fishing gear, as well as active or direct interventions, such as coral transplantation (Edwards and Gomez 2007). However, it should be emphasized that most active coral restoration actions are currently restricted to small spatial scales (for example, less than one square kilometers) and are currently unlikely to achieve ecological outcomes at the scales that reefs function and widespread reef degradation typically occurs (for example, greater than one square kilometer). Therefore, coupling active restoration with improved reef management strategies (for example, water quality, overfishing, and habitat protection) will be essential for meaningful long-term restoration success of degraded reefs. Most restoration projects (about 90 percent) focus on biological coral recovery with less than 20 percent designed with coastal protection benefits in mind (Fabian et al. 2014). Active restoration actions relevant to maintaining or improving the coastal defense service of coral reefs include biological restoration, physical restoration, and artificial reefs (Figure 3.5).

Active biological restoration focuses on recovering or rebuilding the coral species diversity and structure of a degraded reef-coral ecosystem. Stony coral populations are seen as the essential keystone species of the coral reef ecosystem, thus most restoration focuses on them and not on sponges, soft corals, and other mobile and sessile invertebrates that are also part of the reef ecosystem. The most common biological restoration intervention has been the direct in-situ transplantation of stony corals from donor reef sites to degraded reef sites. The establishment of an underwater coral nursery (either in situ or ex situ) can improve survivorship of transplants by reducing stress and stabilizing them before outplanting. Further, donor colonies can be subdivided into smaller colonies through asexual fragmentation thereby increasing the number of transplants. The size of coral outplants positively increases survivorship. Another biological restoration technique that has been successfully applied is the collection of coral gametes and sperm using fine-mesh nets placed around corals during periods of spawning. Settlement of the fertilized coral planulae onto small limestone tiles or fragments is done in a lab or in situ over a period of 24 to 72 hours. Settled coral spat are then seeded onto the degraded reef site, although survivorship is often very low compared to coral nursery efforts that transplant larger-sized corals. The costs and benefits of each of these proven techniques vary and many of them are still largely within the academic sector and not yet adopted by managers and policy makers.

Physical restoration involves repairing or adding to the structural integrity of the reef framework, typically with some combination of limestone and cement. The structural integrity of the reef (width, height) is one of the most important features to consider in the context of coastal defense. Acute physical impacts to the reef crest result from ship groundings, coral mining, blast

Figure 3.5: Underwater Coral Farming Techniques

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. Without active physical restoration interventions, the degraded reef-crest surface deteriorates further from secondary impacts. For example, 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. Coral reef damage-response plans with provisions for assessing damage, removing grounded objects, or cleaning (in cases where removal is not feasible) only exist in some countries and territories. Further, the legal frameworks for applying fines to cover the costs for physical restoration are often weak or nonexistent. 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).

Related to physical restoration, such artificial structures as limestone blocks, rock piles, molded cement, steel, wood, tires, and other materials are placed on the seafloor. The majority of artificial reef projects have been designed for fisheries production, tourism, or coral regeneration (Fabian et al. 2014). When used for coastal defense, artificial structures immediately increase reef relief and topographic complexity where they are placed, providing direct and short-term wave and erosion reduction benefits. However, artificial structure projects are riskier than strictly biological restoration projects. Poorly designed structures can become dislodged during storms, break apart, and cause further damage to the reef and coastal infrastructure. They can pose both a navigational hazard and an aesthetic impact to the area. Detailed environmental impact assessments and permits from municipal and national permitting agencies and the local community are essential. Overall, artificial structure projects require detailed planning and should incorporate the professional expertise of coastal engineers and restoration specialists in their design and construction (Sheppard and Gomez 2007).

3.6| Engineered Structures

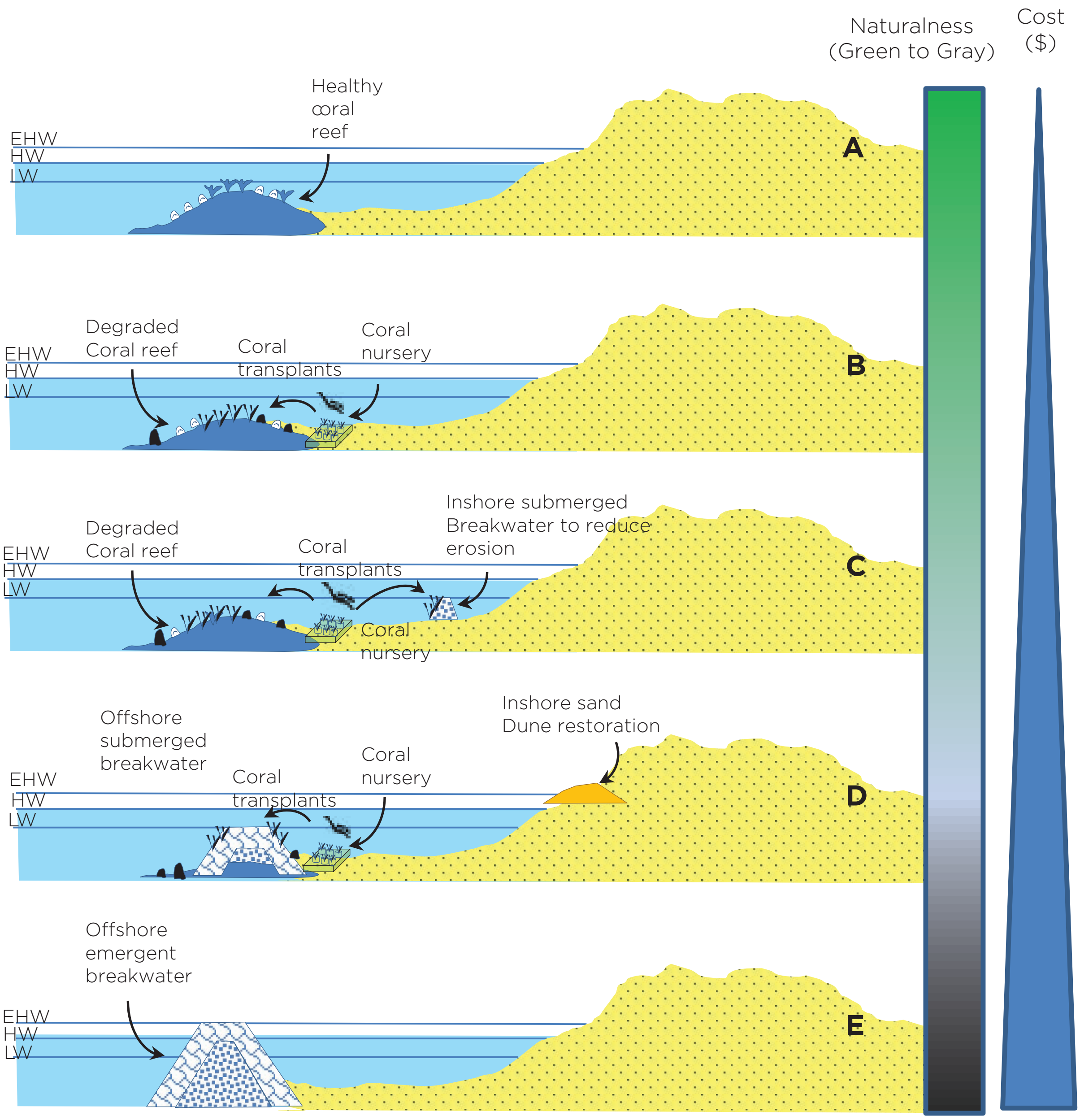
Engineered structures designed to reduce wave energy in developed coastal areas include a variety of riprap, breakwaters, and groins composed mainly of rock and concrete (for example, USACE 2002). A main difference of engineered structures from artificial reefs is that engineered structures are primarily designed to meet the demand for people living along the coasts with limited regard to natural benefits. Indeed, 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 breakwaters and groins can further degrade coastal habitats and displace erosion problems to other sections of coastline. Engineered hard structures can also require substantial constructions and annual maintenance costs. Two of the more important design considerations for engineered structures that influence the natural outcomes include placement and materials.

The placement of engineered structures on the seabed is one of the most critical aspects that directly influences wave and current patterns affecting shorelines. Detailed assessment of the existing bathymetry and wave and current dynamics are often necessary to properly design the size and placement of engineered structures. However, high-resolution (less than 1 meter) and accurate bathymetry data to enable such analyses is often lacking in most tropical island location. The result can be poorly located structures or overbuilding with large footprints, all of which can have further negative impacts on the reef ecosystem. Traditional or gray breakwaters built for marinas or in front of hotel beaches may be built well above mean high tide mark and have few breaks or gaps to enable circulation and flushing critical to support marine life. Outer breakwater walls constructed of either precast concrete modules or large armor rock weighing several tons each often require large barges and deep-water access, which can cause other secondary impacts, such as dredging. Traditional artificial breakwaters are also often constructed in sandy back-reef settings where they may sink over time, losing their defensive function and requiring higher maintenance costs. Advances in the use of geotextiles to underlay artificial structures have addressed some of these issues, but burial by horizontally shifting sand may make these sandy back reef areas less suitable for biological growth.

The material used in engineered reef structures is also critical to their overall performance (durability and stability) and influences their function with respect to attracting aquatic organisms and compatibility with the marine environment (Lukens and Selberg 2004). Large armor stones or precast concrete units are the most commonly used materials for traditionally built breakwaters for waves of 5 meters or more (Palmer and Christian1998). Other commonly available materials, such as used tires, fly ash, and plastic, are no longer favored because they can leach chemicals or must be anchored securely because of their light weight. Of increasing preference are nature-based materials incorporating 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 (Guilbeau et. al. 2003). More than 44 types of artificial "modules" have been patented in the United States alone (Lukens and Selberg 2004). The most common artificial reef modules applicable to coastal defense are Reef Balls™ constructed of concrete (often pH-neutral), Ecoreefs ™ made from ceramic, and BioRock™ constructed of steel with added electro-deposition (UNEP, 2009). Although designed more for reef restoration purposes, these modules and materials are increasingly being applied by coastal engineers for wave reduction and erosion control purposes. Reef Balls™ have now been used in a variety of coastal defense applications with more than 500,000 deployed worldwide. As reviewed by Fabian et al. (2014), most of these materials and techniques are expensive and do promote biological encrustation, but lack evidence of their longer-term durability and function for coastal defense applications. In addition, there are few examples of these artificial modules used in environments with high wave energy.

There is a growing recognition within the coastal engineering field that building with nature, as opposed to against it, can provide significantly greater benefits overall (for example, USACE 2013). Factors for incorporating nature into engineered structures for coastal defense include (i) considering the biomorphology and geohydrology of the seabed, (ii) taking into account existing and potential nature values, and (iii) making use of materials and forces present in nature (Waterman 2008). Engineered breakwaters designed with natural principles and restoration in mind to emulate the natural coral reef value and function may be considered "softer" or "greener" (Figure 3.6) and may have a broader positive restoration benefit. Design characteristics may include a smaller footprint (both extent and width), lower and more natural height (for example, submerged rather than emergent), and gaps or breaks between structures to promote flushing and circulation. The placement of the structures may also be dictated more by the natural geomorphology of the reef platform where biological growth may be more favored. Materials for green breakwaters could include natural limestone blocks or stones from the area that provide a variety of voids or spaces to promote internal and external colonization and provide habitat. The profile, shape, and materials of the breakwater may also promote coral growth and encrustation by crustose coralline algae over time. Transplanting affected live coral fragments back to the breakwater structure after construction might also speed up the colonization process. The Nature Conservancy is currently involved in a pilot project to design and construct a natural submerged breakwater that promotes coral and crustose coralline algae colonization in a shallow high-energy reef setting in Grenada.

Figure 3.6: Solutions to Wave Attenuation in Tropical Waters



As coastal engineering moves toward more sustainable, nature-based designs, advances in materials are also enabling a more-flexible approach to the hard infrastructural for coastal defense (Figure 3.6; see Temmerman et al. 2013 and references therein). Although there will be tradeoffs compared to traditional breakwaters, these more natural submerged breakwaters can still provide significant wave protection and beach sand retention benefits with the added benefits of fisheries production, tourism, and biodiversity. While it is encouraging to see greener engineering approaches to coastal defense, they should not be seen as a substitute for healthy coral reefs that can accrete and keep up with sea level rise over time. Development designs that are more holistic in their thinking beyond just the immediate construction footprint are necessary. Including the preservation of intact healthy reefs with reef restoration and coastal zone management in project designs will help address some of the longer-term issues that are causing declines in coral reefs.

3.7| Cost Effectiveness of Coral Reef Restoration

Ferrario et al. (2014) provide insight into the cost effectiveness of coral reef restoration when compared to the building of traditional breakwaters. They showed that the observed wave-attenuation values by coral reefs in the field were similar to those of constructed low-crested breakwaters. In their review they found that the typical costs of building tropical breakwaters ranged from $456 to $188,817 per meter with a median project cost of $19,791 per meter. These values were largely derived from U.S. Army Corp of Engineers projects. The costs of structural coral reef restoration projects were $20 to $155,000 per meter with a median project cost of $1,290 per meter. On average, reef restoration was significantly less expensive than building tropical breakwaters.

The findings from Ferrario et al. (2014) are consistent with recent analyses from the re-insurance industry on the economics of climate adaptation in eight Caribbean nations (CCRIF 2010). They examined the costs and benefits of 20 approaches for coastal risk reduction, including adaptation, reef restoration, engineered defenses, and policy changes. They found that reef restoration was always more cost effective than breakwaters across all eight nations. Moreover, in seven of eight nations, reef restoration was one of the most cost effective of all approaches.

3.8| Conclusions

Coral reefs are shown to be efficient natural breakwaters that can form an important first line of defense against natural threats for coastal nations. Estimates indicate that more than 200 million people benefit from reduced risk of coastal flooding as a result of coral reefs. Improved methodologies and higher resolution data sets, such as bathymetry, will allow a better accounting of a coral reef's true economic "risk reduction" value. Reducing threats to coral reefs and improving management efforts offer the most cost-effective solutions to retaining a reef's coastal protection services. Coral reef restoration science continues to improve and can provide effective solutions to coral reef degradation at small spatial scales, particularly in areas near large population centers. Combining coral enhancement and nature-based artificial structures into sustainable coastal defense designs can provide multiple benefits over traditional gray designs. Restoration projects that incorporate coastal community values into the overall design can also contribute to longer term success.

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Appendix 3.1: Studies that Measured Wave Energy Reduction by Coral Reefs (Adapted from Ferrario et al. 2014)

Site	Reef environment	Variable unit	Treatment mean	Treatment error	Control mean	Control error	Author	Year
Tague Reef, St. Croix, U.S. Virgin Island	C	$J\ m^{-2}$	38.92	13.71	117.53	37.66	Lugo-Fernandez et al.	1998
Great Pond Bay, St. Croix, U.S. Virgin Island	C	$J\ m^{-2}$	159.17	70.28	420.90	103.50	Lugo-Fernandez et al.	1998
Kaneohe Bay, Oahu, Hawaii	C	$J\ m^{-2}$	318.50	73.68	2906.36	478.32	Lowe et al.	2005
Australia	C	%	34.83	14.12	100.00	0.00	Kench and Brander	2006
Kaneohe Bay, Oahu, Hawaii	C	$J\ m^{-2}$	433.38	110.48	5081.56	2837.96	Lowe et al.	2009
Kaneohe Bay, Oahu, Hawaii	C	$J\ m^{-2}$	1130.68	257.20	7894.92	4614.06	Lowe et al.	2009
Sandy Bay, Ningaloo Reef, Australia	C	$J\ m^{-2}$	125.54	98.46	2241.13	1849.85	Pomeroy et al.	2010
Sandy Bay, Ningaloo Reef, Australia	C	$J\ m^{-2}$	78.53	82.14	1419.26	1156.23	Taebi et al.	2011
Ipan Reef, Guam	C	$J\ m^{-2}$	52.74	62.07	2583.51	2908.73	Pequignet et al.	2011
Mokuleia, Oahu, Hawaii	C	$J\ m^{-2}$	3134.68	1989.23	3927.86	2634.78	Filipot and Cheung	2012
John Brewer Reef, Australia	F	$J\ m^{-2}$	191.40	98.74	437.10	236.69	Hardy and Young	1996
Great Pond Bay, St. Croix, U.S. Virgin Island	F	$J\ m^{-2}$	41.02	20.21	159.17	70.28	Lugo-Fernandez et al.	1998
Yongshu Reef, Nansha Islands, China	F	%	58.94	2.88	100.00	0.00	Zhu et al.	2004
Yongshu Reef, Nansha Islands, China	F	%	55.85	2.89	100.00	0.00	Zhu et al.	2004
Kaneohe Bay, Oahu, Hawaii	F	$J\ m^{-2}$	42.40	22.00	253.82	136.72	Falter et al.	2004
Warraber Island, Australia	F	$J\ m^{-2}$	30.58	23.78	215.43	96.79	Brander et al.	2004

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Appendix 3.1: Studies that Measured Wave Energy Reduction by Coral Reefs (Adapted from Ferrario et al. 2014) *(continued)*

Site	Reef environment	Variable unit	Treatment mean	Treatment error	Control mean	Control error	Author	Year
Kaneohe Bay, Oahu, Hawaii	F	$J\ m^{-2}$	58.58	38.62	318.50	73.68	Lowe et al.	2005
Australia	F	%	7.83	9.72	34.83	14.12	Kench and Brander	2006
Australia LEI	F	$J\ m^{-2}$	89.95	73.18	116.68	58.96	Jago et al.	2007
Warraber Island, Australia	F	$J\ m^{-2}$	112.81	74.38	816.29	682.73	Samosorn and Woodroffe	2008
Hulhudhoo Reef, South Maalhosmadulu Atoll, Maldives	F	$J\ m^{-2}$	75.41	40.12	74.33	32.51	Kench et al.	2009
Hulhudhoo Reef, South Maalhosmadulu Atoll, Maldives	F	$J\ m^{-2}$	33.96	28.54	40.40	10.78	Kench et al.	2009
Hulhudhoo Reef, South Maalhosmadulu Atoll, Maldives	F	$J\ m^{-2}$	5.68	3.51	6.64	2.10	Kench et al.	2009
Hulhudhoo Reef, South Maalhosmadulu Atoll, Maldives	F	$J\ m^{-2}$	8.25	2.98	6.59	1.49	Kench et al.	2009
Sandy Bay, Ningaloo Reef, Australia	F	$J\ m^{-2}$	24.64	24.27	125.54	98.46	Pomeroy et al.	2010
Ipan Reef, Guam	F	$J\ m^{-2}$	2.63	4.91	52.74	62.07	Pequignet et al.	2011
Mokuleia, Oahu, Hawaii	F	$J\ m^{-2}$	179.09	75.85	3134.68	1989.23	Filipot and Cheung	2012
Derawan Island, Indonesia	F	$J\ m^{-2}$	66.49	45.37	201.10	18.10	Christianen et al.	2013
Majuro Atoll, Marshall Islands	F	$J\ m^{-2}$	258.76	170.93	281.01	160.44	Ford et al.	2013
Mtsanga Gouela Beach	F	$J\ m^{-2}$	531.56	173.27	832.23	323.33	Jeanson et al.	2013
Dhakandhoo, South Maalhosmadulu, Maldives	F	$J\ m^{-2}$	105.49	53.06	151.75	77.81	Mandlier	2013
Kandumeygalaa, Huvadhoo, Maldives	F	$J\ m^{-2}$	47.02	12.02	43.28	17.33	Mandlier	2013

(continued on next page)

Appendix 3.1: Studies that Measured Wave Energy Reduction by Coral Reefs (Adapted from Ferrario et al. 2014) *(continued)*

Site	Reef environment	Variable unit	Treatment mean	Treatment error	Control mean	Control error	Author	Year
Red Beach, Whangaparaoa Peninsula, New Zealand	F	$J\ m^{-2}$	60.51	19.29	744.15	330.00	Ogawa	2013
Flume (model of Minatogawa fishery port, Japan)	R	$J\ m^{-2}$	0.48	0.29	9.58	8.83	Nakaza and Hino	1991
Flume (model of Hayman Island, Australia)	R	$J\ m^{-2}$	1556.55	1504.78	7805.67	5297.21	Gourlay	1994
Great Pond Bay, St. Croix, U.S. Virgin Island	R	$J\ m^{-2}$	41.02	20.21	420.90	103.50	Lugo-Fernandez et al.	1998
Molokai, Hawaii	R	$J\ m^{-2}$	5.86	6.26	138.86	67.13	Storlazzi et al.	2004
Kaneohe Bay, Oahu, Hawaii	R	$J\ m^{-2}$	58.58	38.62	2906.36	478.32	Lowe et al.	2005
Australia	R	%	7.83	9.72	100.00	0.00	Kench and Brander	2006
Puerto Morelos	R	$J\ m^{-2}$	1151.49	1563.07	38775.63	56512.52	Blanchon et al	2010
Sandy Bay, Ningaloo Reef, Australia	R	$J\ m^{-2}$	24.64	24.27	2241.13	1849.85	Pomeroy et al.	2010
Ipan Reef, Guam	R	$J\ m^{-2}$	2.63	4.91	2583.51	2908.73	Pequignet et al.	2011
Lady Eliot Island, Australia	R	$J\ m^{-2}$	71.23	39.69	3307.31	2066.16	Haung et al.	2012
Mokuleia, Oahu, Hawaii	R	$J\ m^{-2}$	179.09	75.85	3927.86	2634.78	Filipot and Cheung	2012
Dapani Beach, Mayotte	R	$J\ m^{-2}$	60.59	42.63	899.46	641.56	Jeanson et al.	2013
Trevani Beach, Mayotte	R	$J\ m^{-2}$	41.90	70.71	1026.45	1405.60	Jeanson et al.	2013

4| Ecosystem Service and Coastal Engineering Tools for Coastal Protection and Risk Reduction

Kristy J. Kroeker,[c] Borja G. Reguero,[c,d] Pamela Rittelmeyer,[c] and Michael W. Beck[d]

4.1| Summary

This chapter provides an overview of several common tools and approaches used to assess risks from flooding and erosion, and to estimate coastal protection benefits from natural habitats. The methods for estimating the role and value of natural habitats in coastal protection and risk reduction are diverse but mainly fall into two broad categories of index-based approaches and process-resolving approaches (including numerical models) and vary considerably in their ease of use, complexity, and accuracy. This guidance note reviews both (i) the common coastal ecosystem service tools and (ii) the engineering tools, models and approaches for estimating coastal risks and the role of habitat (and other infrastructure) in reducing erosion and flooding to avert economic and social damages. It highlights how these approaches can address the role of coastal habitats in reducing erosion and flooding to avert economic and social damages.

This guidance note recommends using process-based approaches in general and further recommends an Expected Damage Function (EDF) approach for valuing the coastal protection services from reefs and mangroves. The EDF is adapted from approaches commonly used in engineering and insurance to assess risks and benefits. There are five core steps to estimating coastal protection benefits from any kind of infrastructure: (i) estimate offshore hydrodynamics (wind, waves, and sea levels); (ii) Estimate nearshore hydrodynamics; (iii) Estimate effects of coastal structures (habitat) on hydrodynamics; (iv) Estimate flooding or erosion; and (v) Assess expected and averted damages (that is, value coastal protection benefits).

Together, these five steps constitute a process of sequential steps that allow assessment of coastal habitat protection benefits in terms of damages averted by conserving or restoring the habitats. Engineers commonly use these steps to estimate coastal hazards and assess infrastructure alternatives for risk reduction (for example, dikes); the insurance industry also uses them to assess climate risks and adaptation alternatives.

4.2| Introduction

Ecosystems support human societies in many ways. For example, ecosystems in the coastal zone support fisheries, protect coastlines, and provide opportunities for tourism and recreation. Ecosystem service tools have been developed to model the roles that natural habitats play in supporting human livelihoods and wellbeing (Bagstad et al. 2013; Vigerstol and Aukema 2011). Many tools provide explicit spatial maps of ecosystem services that allow decision makers to evaluate trade-offs between development and protection of natural habitats (Naidoo et al. 2008). Such methods for estimating the economic value of ecosystem services can also incorporate costs avoided or savings afforded by natural habitat, which serve as additional aids in making decisions (Daily et al. 2009).

Estimates of coastal protection services are often derived by calculating the effect of natural habitats on flooding or erosion. Several tools and approaches model the coastal protection and risk reduction services from natural habitats, such as coral reefs and mangroves. These tools and

c University of California Santa Cruz.
d The Nature Conservancy.

frameworks can be separated into two main categories based on their approach to estimating coastal protection: index-based approaches and process-resolving approaches.

Index-based approaches use estimates of exposure and vulnerability to assess risk and risk reduction benefits. These indices can be (re)calculated using different configurations of natural habitats or other environmental conditions (for example, sea level) to estimate potential changes in risk or benefits. For example, the Coastal Vulnerability Module of InVEST (Arkema et al. 2013) uses an index-based approach to create an index to assess shorelines most at risk to flooding. It scores seven variables—such as winds, wave surge, sea level, and type of habitat—on a scale of one to five to indicate exposure of the shoreline.

Process-resolving approaches, on the other hand, define meteo-oceanographic variables, such as waves, storm surges, currents, tides and sea level, and examine coastal processes, such as sediment transport and interactions between waves and structures to assess risks and the value of habitats in reducing exposure. Process-resolving approaches can be further delineated into analytical approximations and numerical models. Analytical approximations of coastal processes or semi-empirical formulations have low computing capacity requirements and are affordable to implement at large scales (for example, propagation of waves over vegetation fields, such as Mendez and Losada, 2004; or run-up formulations, such as Nielsen and Hanslow 1991). Numerical models can resolve coastal processes with higher accuracy. Depending on the scope of the study, various numerical models can be applied to deal with the different processes involved in coastal hazards and risk reduction.

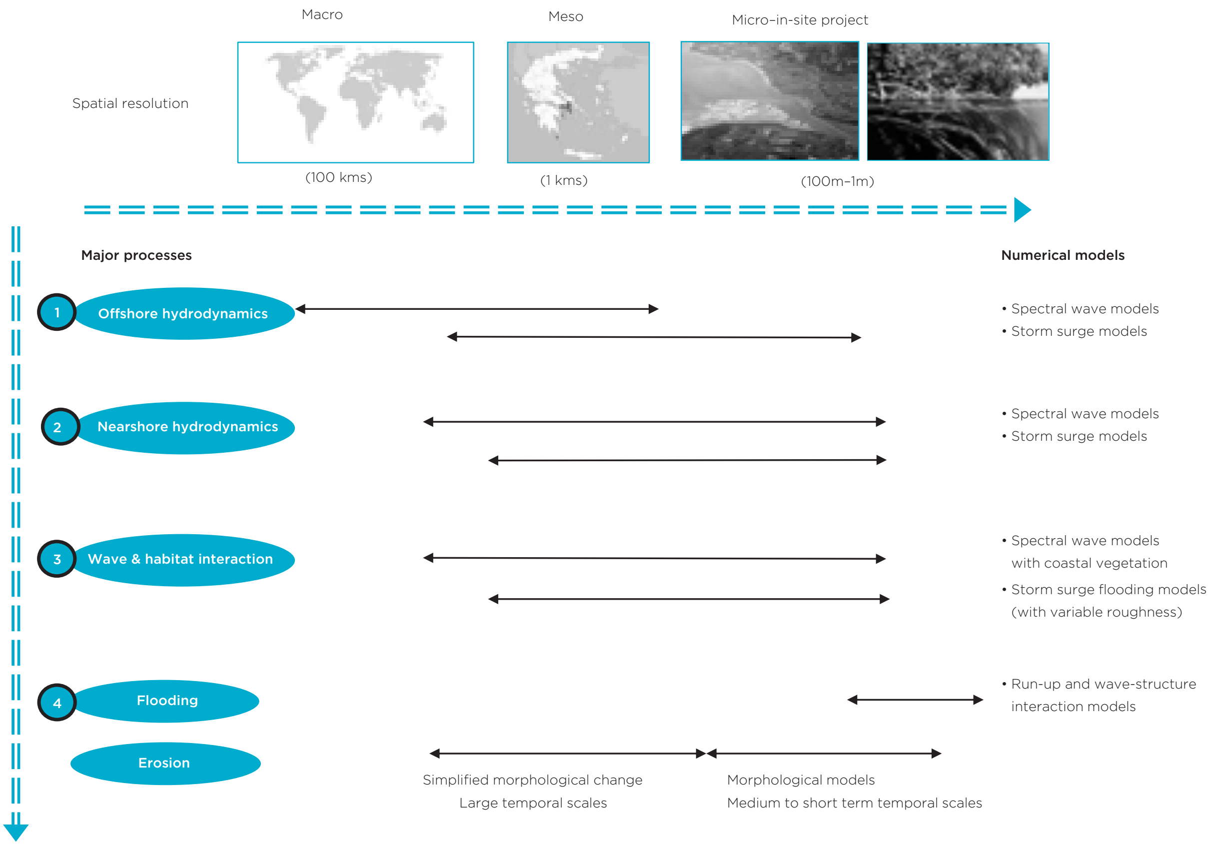
More complex and accurate tools require more technical expertise and computing capacity, which can limit the geographic scale at which process-resolving tools are used. Thus, the geographic scope of the analysis often defines which approach is used to estimate coastal risks and protection benefits (Figure 4.1). Global or national-scale analyses often use index-based approaches that combine hydrodynamic (for example, mean significant wave height), geophysical (for example, geological features), and socioeconomic (for example, population density) data into a unique metric or index (for example, USGS Coastal Vulnerability Index; InVEST Coastal Vulnerability Index). Local-, regional-, and some global-scale studies use process-resolving approaches that numerically model factors, such as wave propagation, onshore flooding, or sediment movement. Process-resolving approaches provide more detailed results than integrated indices; however, they require more technical expertise. Thus, process-resolving approaches are sometimes included in large-scale assessments of coastal protection values, benefits, and services by using analytical equations for ideal conditions or semi-empirical models, but these approaches are less accurate than those approaches that use numerical models at a local scale.

A number of generalized tools use index-based or process-resolving approaches for estimating coastal risks and coastal protection benefits (Appendix 4.1). Many approaches sit between general ecosystem service tools and more complex coastal engineering approaches that rely upon numerical models. Within the range of process-resolving models, however, tools can differ substantially in complexity and accuracy.

4.3| Methods and results

First, this chapter reviews a range of ecosystem service tools and approaches that estimate coastal protection and risk reduction by natural habitats, such as mangroves and coral reefs (Appendix 4.1). It highlights both general and multi-ecosystem service tools, as well as tools or approaches specifically focused on estimating coastal protection services. For each tool, it examines the aim, scale, data needs, and ease of use of each tool. It also examines case studies and documentation pertinent to coastal protection applications of each tool.

Figure 4.1: Processes that need Resolution to Estimate Coastal Protection Benefits and the Types of Models that Work at Different Scales



Although numerous tools have been developed to map vulnerability and exposure to coastal hazards, such as storm surges and sea level rise, this chapter specifically emphasizes tools that examine how natural habitats affect coastal protection services. It focuses on tools that are publicly accessible, namely: InVEST, ARIES, MIMES, Coastal Resilience, RiVAMP, Climada, and the Coastal Capital Project Framework. It does not discuss other well-known ecosystem service tools, because at publication time these tools could not easily be used to model coastal protection from natural habitats (for example, Atlantis; Benefits Estimation Toolkit; EcoServ; Ecosystem Portfolio Model; Envision; ESR; SERVES). Tools that are primarily used for visualizing hazards are not reviewed (for example, Surging Seas or National Oceanic and Atmospheric Administration [NOAA's] Sea Level Rise Viewer), but could be used to identify areas for more in-depth modeling of coastal protection using other tools. A more comprehensive list of visualization tools can be found at the Digital Coast portal.[2]

Second, this chapter describes the steps involved in more in-depth, coastal engineering-based approaches for examining how coastal structures (natural or artificial) affect flooding and erosion. It highlights some of the most common coastal engineering tools and approaches used to estimate risks and assess alternative scenarios for risk reduction or coastal protection. Some of these tools either already include natural habitats and address those habitats' role in erosion and flooding reduction or could be easily modified to do so. In addition, the chapter discusses numerical models in coastal engineering practice that can be used for in-depth examinations of

2 http://coast.noaa.gov/digitalcoast/.

the role of reefs and mangroves in coastal protection or to design habitat restoration projects for coastal protection.

4.4| General Ecosystem Service Tools—Measuring Multiple Ecosystem Services

Integrated Valuation of Ecosystem Services and Tradeoffs (InVEST)

InVEST was developed to model and map a wide variety of ecosystem services within a specified geography to help users understand the trade-offs in ecosystem services associated with management or policy decisions (Sharp et al. 2014). The Marine InVEST tool focuses specifically on ocean and coastal ecosystem services and can be paired with a valuation module to estimate economic gains or losses based on various habitat management scenarios. Marine InVEST provides information on how the protection or restoration of coastal ecosystems, such as coral reefs, marshes, or mangroves, reduces both societal risks and economic costs in the coastal zone. There are two modules within InVEST that are relevant to coastal protection and risk reduction: the Coastal Vulnerability Module and the Coastal Protection Module.

The Coastal Vulnerability Module is an index-based tool that maps areas of high or low vulnerability to coastal hazards. The vulnerability of a shoreline is based on seven variables: geomorphology, relief, presence of natural habitats, sea level rise, as well as wind, wave, and surge exposure.[3] While the tool does not provide quantitative valuation of protection (for example, economic values for shoreline protection from natural habitats), the change in shoreline exposure score can be examined relative to the density of people and property potentially affected (for example, Arkema et al. 2013). The Coastal Vulnerability Module is a relatively general tool compared to the Coastal Protection Module, and it does not take into account local ocean processes, such as sediment transport.

Arkema et al. (2013) used the Coastal Vulnerability Module to estimate the vulnerability of the U.S. coastline to storms and sea-level rise with and without natural habitats. The authors created a coastal hazard indicator and identified areas of highest vulnerability along the U.S. coastline. In addition, the Coastal Vulnerability Module has been employed in Monterey Bay, California, to demonstrate how the protection of coastal dunes and wetlands could reduce the vulnerability of coastal infrastructure, populations, and farmland to flooding and erosion from ocean storms or rising sea levels (Langridge et al. 2014). The Coastal Vulnerability Module has also been used to rank risk of coastal hazard in areas of Rhode Island, and to examine vulnerability from destruction of mangrove forests in the Bahamas.

The Coastal Protection Module models how reefs (coral and oyster) and wetlands (mangroves, marshes, or seagrass) attenuate waves and reduce erosion or flooding.[4] It is a process-based tool that allows users to develop scenarios and examine impacts on coastal protection benefits. The output is easily accessible (for example, wave height or water levels before and after a management action), and can include a table summarizing the economic values of damages to coastal properties and infrastructure that could be avoided through natural habitat protection or restoration.[5] Estimates of the beach nourishment costs accrued or avoided due to the presence or absence of natural habitats are in development.

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[3] http://www.naturalcapitalproject.org/models/coastal_vulnerability.html.

[4] http://www.naturalcapitalproject.org/models/coastal_protection.html.

[5] http://ncp-dev.stanford.edu/~dataportal/invest-releases/documentation/current_release/coastal_protection.html.

The Coastal Protection Module requires relief data about the coastal zone (for example, bathymetry and topography) and wind-wave input from past records of wind and wave heights for the given location. General wind-wave input can be obtained through Operational Wave datasets (for example, NOAA WAVEWATCH III databases[6] or the European Centre for Medium-Range Weather Forecasts) or the different wave re-analyses available worldwide (for example, Reguero et al. 2012; Rascle and Arduin 2013). All other inputs require some parameterization. Some people and property asset data are available through Marine InVEST, although the general asset data can be improved upon with finer-scale data for given locations. For example, InVEST provides global population data, but the user is encouraged to input more detailed census data.

The first step of the Coastal Protection Module is to run the submodel Profile Generator to obtain a cross-shore profile that contains bathymetry and backshore information for a given location. A Digital Elevation Model with a vertical elevation referenced to Mean Lower Low Water is necessary, if the user wants the GIS to cut a cross-shore transect. The user may input more detailed information on bathymetry and coastal habitats.

The second step of the Coastal Protection Module is to run the submodel for nearshore waves and erosion. The user can choose to input wave height and wave period values, or wind speed, fetch distance, and water depth. In order to compute economic values for costs accrued or avoided due to natural habitats, the model requires the length of the natural habitat types, coverage, and management actions (for example, restoration or dike building) to calculate the extent of land loss or flooding. The economic valuation also requires information about local property values, typical return period of storms in the study area, appropriate discount rate (that is, accounting for the future value of today's dollar), and the number of years the user intends to value the coastal protection provided by the habitat.

Although early versions of InVEST required ArcGIS, most modules now use free, open-source code in a stand-alone platform that can be launched in a Windows operating system. The Coastal Protection Module, however, still requires ArcGIS to run the model (Sharp et al. 2014). Both InVEST modules are well documented. The interface and output are user-friendly, requiring less training than many other tools.

Mobile Bay, Alabama, Puget Sound, Washington, and the Florida Keys are using the Coastal Protection Module to examine wave attenuation and habitat restoration options. Further documentation for the use of the *Coastal Protection Module* is in development, including examples in Galveston Bay, Texas and the Hawaiian Islands (Guannel pers. comm.).

Artificial Intelligence for Ecosystem Services (ARIES)

ARIES is a general ecosystem service tool developed to model multiple ecosystem services, including, but not limited to, risk reduction from coastal flooding. ARIES differs fundamentally in its approach from InVEST because it does not use biophysical relationships to model coastal risk reduction. Instead, it uses probabilistic relationships based on historical data to spatially link biophysical units (for example, tons of sediment) and abstract units (for example, soil retention).

ARIES is flexible enough to accommodate multiple ecosystem services, and it allows the user to spatially map the uncertainty associated with the model output, a feature not available in many of the other ecosystem service tools. In addition, ARIES is being developed to include generalized models so it can be used in data-poor contexts where local data are not available (Villa et al. 2014).

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6 http://polar.ncep.noaa.gov/waves/index2.shtml.

ARIES is designed to include several approaches to estimate the economic value of ecosystem services. In one approach, the user enters values for multiple services, which are then paired with user-defined priority-based weights. Alternatively, a future version of the tool is being developed to include monetary values from an ecosystem services database so that users can access economic valuation studies from their region (Bagstad et al. 2011). Information on ecosystem service flows can be incorporated to translate previously assessed economic values of specific benefits into valuations as required by the user.[7]

The Coastal Flood Regulation Module is the most relevant module in ARIES for modeling coastal protection from coral reefs and mangroves. It uses historical data from storms to build statistical relationships between wave exposure, coastal habitats, and the impacts on people and infrastructure. Although ARIES relies on Bayesian modeling, it also incorporates some proxies for coastal processes. For example, storm surge values are defined as high when there are high winds, low barometric pressure, and shallow water depths. The output from the Coastal Flood Regulation Module includes the storm surge height above sea level for a simulated future storm (Johnson and Bagstad 2012), as well as the number of people or assets spared from coastal flooding.

ARIES currently does not provide an economic valuation of these particular ecosystem services, but the developers are working to include them in future versions. Other future improvements might include shifts in storm direction.

At this time, the Coastal Flood Regulation Module in ARIES is still at a proof-of-concept stage, where the output may be less reliable than other tools. While the reliability of the module might benefit from the inclusion of local data and additional biophysical process models, these enhancements are likely to decrease its usability.

At present, ARIES is an open-source, stand-alone modeling platform still in development. The developers intend to create a Web-based tool in the future (Bagstad pers. comm.). Currently, use of the tool requires participation in an ARIES training course or a formal partnership with the ARIES development team.

ARIES, which has both technical and nontechnical interfaces, does not require special programming skills. The user starts by choosing the geographic region. The model then presents a rule engine—a nominal interview process—where the user chooses which data to include. This process allows ARIES to identify the user's priorities and determine which models will aid in making decisions. Users can explore scenarios that vary the availability of the ecosystem service factors. A working knowledge of Bayesian statistics will aid interpretation.

ARIES has been used in several temperate and tropical ecosystems, although there is limited documentation for use in coastal protection. For example, Wendland et al. (2010) examined the role of forests in carbon sequestration and storage, sediment regulation, subsistence fisheries, and coastal flood regulation by linking the terrestrial and marine ecosystem service models to inform planning decision and conservation efforts on the island of Madagascar (Wendland et al. 2010). ARIES is at work in the Chehalis River Basin in Washington to examine the role of natural habitats in flood protection in response to catastrophic riverine floods (Batker et al. 2010). Likewise, Mexico has used ARIES to explore the hydrological services of upstream cloud forests in a small watershed where a payment for ecological services (PES) system is in place.[8]

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7 http://ariesonline.org/about/approach.html.

8 http://www.ariesonline.org/case_studies/veracruz.html.

Multiscale Integrated Models of Ecosystem Services (MIMES)

MIMES is another spatially explicit, general ecosystem service tool. It is publicly available, but is not as well documented as InVEST and ARIES (Bagstad et al. 2013). It is place specific, and a long lead-time is required for first runs in new locations, because a highly technical user or a consultant needs to program it (Bagstad et al. 2013). Early versions of MIMES have been used in Massachusetts, the Mississippi Delta, Texas, Washington, and Russia. It is currently under development in Cambodia with the goal of tracking how humans interact with natural systems over time (Berdik 2014). To date, each module of the application is made for a specific purpose. For instance, the Austin, Texas, project modeled the potential effects of climate change (for example, extreme heat) on human health at a local scale, as well as possible mitigation approaches (Boumans et al. 2014). To date, no documentation exists for the use of MIMES to specifically estimate coastal protection services from natural habitats. Data outputs must be post-processed in GIS to be visualized. The model can also be integrated with R software for more statistical analysis (Boumans pers. comm.).

4.5| General Coastal Risk and Vulnerability Tools

The following general tools are primarily focused on estimating coastal risk reduction. They may consider additional ecosystem services, but do not usually measure them explicitly.

Coastal Resilience tool

The Coastal Resilience tool aims to assess the social and economic risks associated with storms and sea level rise and identify natural and nature-based solutions to help reduce these risks (Ferdana et al. 2010; Gilmer and Ferdana 2012; Beck et al. 2013). The Coastal Resilience tool utilizes ESRI's ArcGIS API for JavaScript. It has a modular plug-in architecture that allows for applications (hereafter, referred to as *apps*) to be developed for specific risk and vulnerability coastal issues and to help identify risk reduction solutions. Several interactive apps help users assess risks from regional to national scales.

i. The Risk Explorer app is based on the Coastal Vulnerability Module of InVEST (Arkema et al. 2013, see above). In addition to the exposure variables considered in Coastal Vulnerability Module, it also incorporates social vulnerability metrics, such as percent of people living below poverty level. It is currently available nationwide in the United States.

ii. The Restoration Explorer app allows users to identify priority areas for reef and wetland conservation and restoration that would reduce social vulnerability from erosion and flooding.

iii. The Coastal Defense app directly measures coastal protection services. It examines how coral reefs, mangroves, marshes, oyster reefs, seagrasses, and dikes can reduce wave height, water level, and loss of fine sediments in coastal areas.[9] It runs a modified version of the Coastal Protection Module from InVEST and provides a user-friendly interface to this module. All of the input parameters required by the Coastal Protection Module are pre-processed, and the user then selects where to run the module (that is which transects), under what conditions (averages, strong storm, or maximum for the area), and can add height or width to reefs and wetlands (that is, design a restoration scenario). The app helps users identify the wave attenuation or coastal protection value of existing reef and wetland habitats and allows users to design restoration solutions and assess their coastal protection values in terms of wave attenuation. The Coastal Defense app provides numerical estimates

[9] A video tutorial is available here: http://youtu.be/VZkstFZedAg.

of the percent reduction in wave height for scenarios with and without natural habitats, but does not currently estimate the economic values accrued or avoided in these scenarios.

The Coastal Resilience tool runs globally and is scalable. That is, there are applications that work globally and then at increasingly greater detail regionally (for example, Mesoamerican Reef), nationally (Grenada, St. Vincent, United States), subnationally (for example, Gulf of Mexico) and locally (for example, Florida Keys). The Coastal Defense app works across all major reef and wetland habitats (that is, the model is general), but it is currently only running at full scale in certain U.S. geographies. It is being developed to work globally (Z. Ferdana pers. comm.) and is rapidly being expanded in tropical geographies. The app is designed on open source technology, and all codes are available on GitHub.[10]

Risk and Vulnerability Assessment Methodology Development Project (RiVAMP)

The RiVAMP provides a framework for estimating disaster and risk reduction from coastal habitats in the coastal zone by incorporating ecosystems and climate change in the risk assessment process. This framework uses a range of numerical and spatially explicit models to highlight how ecological and environmental factors, such as coastal habitats and climate change (for example, sea-level rise and storm surges associated with extreme tropical cyclones), could affect beach erosion, coastal populations, and infrastructure (Chatenoux et al. 2012).

Beyond the attention to coastal ecosystems and environmental factors, the RiVAMP framework considers important social factors in its assessment process, including local livelihoods and environmental governance.

RiVAMP's pilot initiative in Jamaica described the role of coral reefs and seagrasses in risk reduction in Negril, Jamaica—an urban tourist destination with high vulnerability to coastal hazards (UNEP 2010). The pilot study used a combination of numerical and geospatial models to do the following: (i) map coastal ecosystems and beach erosion over time; (ii) numerically model wave and sea-level dynamics over reefs; (iii) establish the effect of ecosystems on beach erosion using multiple regression from 74 beach profiles; and (iv) apply scenarios of sea level rise through model ensembles to estimate exposure to beach loss and flooding. In particular, GIS was used to analyze the widths of the beaches and compare them with the minimum and maximum changes under several sea-level rise and storm-surge scenarios. The RiVAMP study "clearly demonstrate[d] the critical services that coastal ecosystems provide to the Negril beach" (UNEP 2010).

RiVAMP does not provide a user interface, but the approach is replicable using a variety of tools. Essentially, it represents an approach to modeling coastal risk reduction that relies on a combination of tools, data, and expertise. The spatially explicitly nature of the modeling approach requires a GIS platform and, similar to other spatially explicit mapping tools, RiVAMP requires a Digital Elevation Model for the given location. In addition, the user must provide maps of coastal habitats and information about the distribution of ecosystems, as well as the distributions of human population and assets distribution for the location of interest. All other inputs (tides, sea level rise projections, storm surge, wave run-up for population, asset exposure, beach slope, grain size of sand, and wave characteristics for beach erosion) require user parameterization.

Climada

Climada is a tool that can assess risk from wind and storm surge and perform a cost/benefit analysis of risk reduction measures following the Economics of Climate Adaptation

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[10] https://github.com/CoastalResilienceNetwork.

(ECA) methodology (ECA 2009). Climada was not designed to be an ecosystem service tool per se, but it does assess economic losses from coastal hazards and the role of natural habitats (and other measures) in reducing these losses. If the damage avoided because of coastal ecosystems is parameterized in the loss function, Climada can assess the protection value of the ecosystem services provided by coastal habitats. It can include further information on the values of other ecosystem services, such as fisheries, carbon sequestration, and recreation (Reguero et al. 2014). Outputs of Climada include cost/benefit curves of representative adaptation measures, which may be particularly useful for national accounting.[11]

Climada is developed in Matlab, which requires technical knowledge and programming skills. Documentation is available online, in Github,[12] and through demonstrations. Case studies include analyses of risk reduction from tropical cyclones in South Florida, United States, climate adaptation in the Caribbean (CCRIF 2010), and coastal risks and nature-based defenses in the Gulf of Mexico (Reguero et al. 2014).

Coastal Capital Project Framework

The World Resources Institute (WRI) developed a detailed framework to analyze the benefits of coral reefs and mangroves, including their role in shoreline protection. This approach, defined in the Coastal Capital Project (CCP), has been used in five Caribbean nations: Belize, the Dominican Republic, Jamaica, St. Lucia, and Trinidad and Tobago.[13] This series of economic valuation studies is an example of international, national, and regional collaboration using a consistent framework with common rules. It specifically addresses coastal protection from coral reefs and mangroves, among other services, through analysis of scenarios of indicators or indices.

As an example, the analysis in Jamaica used a detailed hydrodynamic model to determine the relationship between coral reef height and physical condition on wave attenuation in three representative areas of coastline. It then used GIS to assess reef types, complexity, and distances to shoreline, as well as land elevation and complexity for the entire island. It next grouped the segments of the coastline with similar reefs to the representative reefs in the detailed hydrodynamic models into categories of coastal protection (low, medium, and high).

WRI developed a guidebook and valuation toolkit for the CCP case studies in the Caribbean. The toolkit includes an Excel spreadsheet to guide the valuation of fisheries, tourism, and marine protected areas and a detailed discussion of how to evaluate shoreline protection with a GIS (WRI 2009). The general process to value shoreline protection includes identifying land that is vulnerable to wave-induced erosion and storm damage based on distance to the shoreline and elevation, identifying coastline that is within a certain distance from coral reefs or mangroves, ranking the physical stability of the shoreline, and estimating the damages to property value avoided when coral reefs or mangroves are present. The case studies were performed entirely in GIS. WRI developed separate GIS-based methodologies to evaluate the benefits of coral reefs and mangroves to fisheries and tourism (WRI 2009; Burke et al. 2008; Cooper et al. 2009). Sheppard et al. (2005) used the CCP to examine the relationship between coral reef decline and increase in beach erosion, with an output into an Excel spreadsheet (Wielgus et al. 2010).

A step-by-step guidebook directs valuation practitioners through the different phases of the process from stakeholder engagement to analysis and outreach, using language suitable for

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11 http://www.iac.ethz.ch/edu/courses/master/modules/climate_risk/climada_manual.pdf.

12 https://github.com/davidnbresch/climada.

13 http://www.wri.org/our-work/project/coastal-capital-economic-valuation-coastal-ecosystems-caribbean/publications#project-tabs.

both economists and noneconomists.[14] The guidebook describes the scoping process, and provides guidance for including the various stakeholders in the process and identifying policy questions. It also leads the user through the process of developing scenarios, choosing a valuation method, accounting for risk and uncertainty, and applying decision support tools. The guidebook concludes by detailing how to clearly communicate the results to decision makers and others. Each phase of the guidebook emphasizes stakeholder engagement.

Summary of general ecosystem services tools and approaches

Each of these tools and approaches can be used to estimate the risk reduction afforded by coastal habitats, although they vary considerably in their data requirements and ease of use (see Appendix 4.1 for a breakdown of these factors). In practice, the Coastal Vulnerability and Coastal Protection modules in InVEST, which form the foundation for the Coastal Resilience tools, are currently the most accessible and widely used tools for estimating risk reduction from natural habitats. Similarly, the Coastal Capital Project Framework represents an accessible framework for linking erosion and flooding damage to economic benefits afforded by risk reduction in broader valuations.

4.6| Engineering Tools and Models: Process-based Approaches for Assessing Coastal Protection

Process-based approaches for estimating coastal protection vary from general approaches to highly detailed numerical models. For all these approaches, there are **five core steps** that are central to estimating **coastal protection benefits** from any kind of infrastructure:

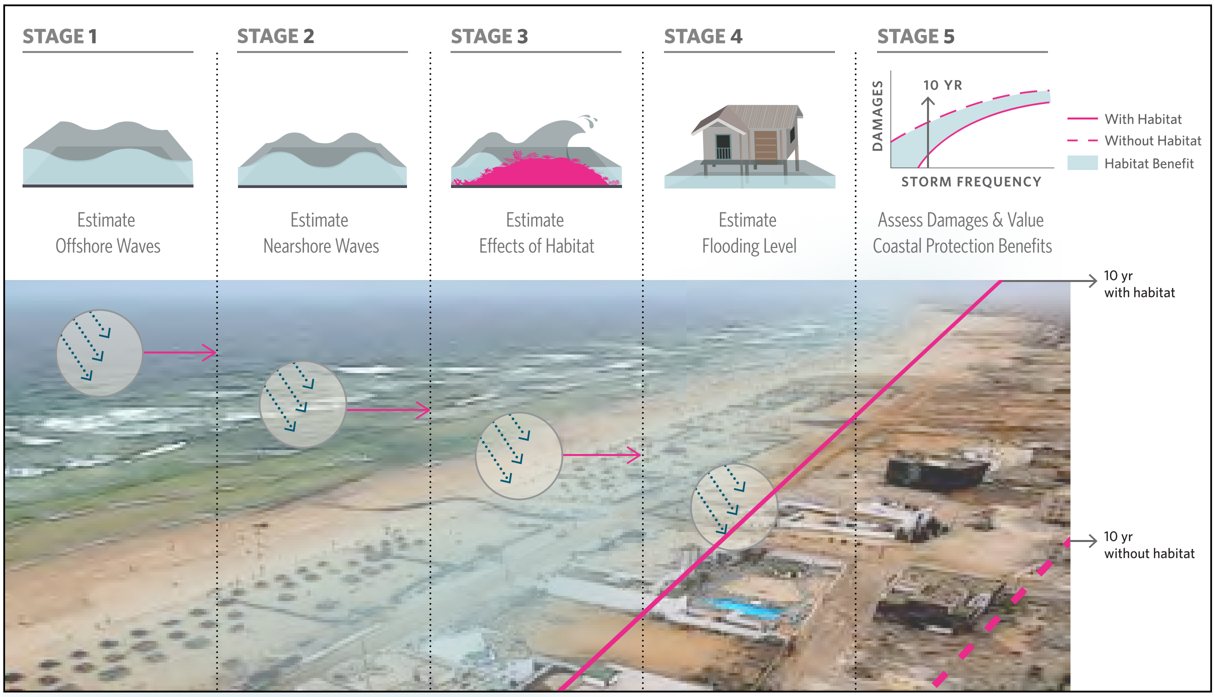
1. **Estimate Offshore Hydrodynamics** (waves and surge)
2. **Estimate Nearshore Hydrodynamics** as they interact with the coastline
3. **Estimate Effects of Coastal Structures (Habitat)** on hydrodynamics
4. **Estimate Onshore Flooding or Erosion**
5. **Assess Expected and Averted Damage**s from Flooding or Erosion (Figure 4.2).

Together, these five steps allow an assessment of coastal habitat protection benefits in terms of damages averted by conserving or restoring the habitats. Each of these five steps represents a different type of problem to be solved, and there is a suite of tools and models for solving each (see Table 4.1 and Appendix 4.2). These steps are commonly used by engineers to estimate coastal risks and assess infrastructure alternatives for risk reduction (for example, dikes), as well as by the insurance industry to assess climate risks and adaptation alternatives (for example, CCRIF 2010; ECA 2009).

These five steps are first described in general and then there are short descriptions of the coastal engineering tools commonly used in steps one to four (Table 4.1). The fifth step (Assess Expected and Averted Damages) is discussed here and also in Chapter 5 on economic valuation. Most of the steps are the same for estimating benefits from any coastal habitat, including reefs and mangroves. The third step addresses the interaction between waves and coastal habitat and the equations are specific to each ecosystem type (that is, the equations for how waves interact with intertidal vegetation are different than the equations for how waves interact with offshore submerged breakwaters or reefs). This section recommends and describes an EDF approach to assessing benefits from habitats (see Barbier 2007), but other approaches for estimating economic values are also possible (for example, replacement costs) as explained in Chapter 5.

[14] http://www.wri.org/publication/coastal-capital-guidebook.

Figure 4.2: Conceptual Diagram of Process-based Steps for the Assessment of Flooding and the Role of Habitats in Flood Reduction



There are two main outputs from this five-step approach. The first product is an assessment of existing risk, which is usually expressed as the EDF, that is, as a relationship between expected damages and storm frequencies (other hazard events such as earthquakes can also be expressed in terms of their EDF). Storm frequencies are often characterized by the likelihood that extreme storm conditions occur on average once every certain number of years and is referred to as the return period of a storm (for example, once in 10-year storm).

The second product from this approach is a comparison of expected damage functions among alternative scenarios, such as different coastal protection alternatives (for example, sea defenses, shoreline restoration) or climate change hazards (for example, sea-level rise). The coastal protection benefits of reef and mangrove habitats can be estimated as the difference in expected damages associated with flooding (or erosion) levels among alternative scenarios. These comparative results are sometimes referred to as averted damages (that is, the differences between expected damages originating in alternative scenarios). Table 4.1 provides a list of many of the coastal engineering tools used to study coastal processes and provides some guidance on how to apply these tools to coral reefs and wetlands for each stage.

Description of steps to estimate coastal protection from habitats:

1. *Estimate offshore hydrodynamics (waves and surge)*

The study of coastal protection starts with the oceanographic conditions that generate waves from wind in deep waters. Coastal applications also require an assessment of winds, waves, mean sea level, tides, and storm surge. Databases and numerical models are available for each of these variables (see Table 4.1). For example, for wave generation there are several models and numerical databases to estimate these terms, such as WaveWatch III (Tolman 2002, 2014) (see Table 4.1).

Table 4.1: Coastal Engineering Models and Tools for Assessing Coastal Protection Benefits. The tools are separated by the process-based steps in Figure 4.2. (Under "Scope," wind waves [short waves] and storm surge [long waves] are differentiated, because they require different modeling approaches

1. Estimate Offshore Hydrodynamics					
Type of Approach	**Scope/Type of Problem**	**Scale of Applicability**	**Ex. of Models**	**Key Considerations**	**Ex. of Applications**
Analytical or semi-empirical approximations	Wave generation	All scales	Hasselmann et al.1976	Approximates the wave generation for a body of water with relatively simple geometry based on: 1. Fetch (distance)-limited conditions 2. Duration (time)-limited conditions	Arkema et al. 2013
	Storm surge generation	Large scales	Dean and Dalrymple 1984	Approximates storm surge for simplified bathymetric profile. Approximates the effect of the sea level pressure and the wind thrust. Inaccurate for local sites and complex local geometries.	Reguero et al. 2014
Numerical modeling	Wave generation[a]	All scales	WW3, WAM, Swan	Spectral wave models can generate waves from wind at any scale. Used for a range of domains, from ocean basins to inner seas or lakes. Requires information from forcings (wind fields), bathymetry, and land domain (coastlines and ice cover). Often, have been pre-run for large domains and long time spans to generate pre-computed atlases (that is, wave re-analyses).[b]	Reguero et al. 2013 Izaguirre et al. 2013 Vatvani et al. 2012 Stockton et al. 2012
	Generation of storm surge[c]	Regional to local scales	SLOSH, ADCIRC, DELFT3D, CEST, ROMS,	Numerical models provide the best approach to computing surges associated with tropical and extra-tropical storms. They generate the surge from the storm meteorological conditions (wind and pressure) at 2D and 3D domains.	Vatvani et al. 2012 Westerink et al. 1992 Kerr et al. 2013a,b Losada et al. 2013 Cid et al. 2014

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Table 4.1: Coastal Engineering Models and Tools for Assessing Coastal Protection Benefits. *(continued)*

Type of Approach	Scope/Type of Problem	Scale of Applicability	Ex. of Models	Key Considerations	Ex. of Applications
1. Estimate Offshore Hydrodynamics					
Sources of data on offshore hydrodynamics	• A comprehensive list of global datasets on sea surface conditions can be found in: *http://www.aviso.altimetry.fr/en/data.html.* • Sources of wave data include wave buoys: for example, *http://www.ndbc.noaa.gov/*; and satellite measurements: example, *http://www.oceanor.com/Services/wwa_info/* • Examples of precomputed wave atlases include Global Ocean Waves (Reguero et al. 2012, 2013), NOAA's operational hindcast (*http://polar.ncep.noaa.gov/waves/index2.shtml*); ERA-20C (*http://www.ecmwf.int/en/research/climate-reanalysis/era-20c*), and WW3 CFSRR Reanalysis (*http://polar.ncep.noaa.gov/waves/CFSR_hindcast.shtml.*). • Information on tide levels can be found at *http://www.oco.noaa.gov/tideGauges.html.* • Databases on storm surge include Surgedat: *http://surge.srcc.lsu.edu/data.html* and Dynamic Atmospheric Correction (DAC) – *http://www.aviso.altimetry.fr/en/data/products/auxiliary-products/atmospheric-corrections/description-atmospheric-corrections.html.* • Data on past storm events can be found at *https://www.ncdc.noaa.gov/stormevents/* and *https://climatedataguide.ucar.edu/climate-data/ibtracs-tropical-cyclone-best-track-data.*				
Tools for statistical analysis of hydrodynamic conditions	A variety of techniques (such as Reis and Thomas 2007), packages, and toolboxes are available for statistical modeling of hydrodynamic conditions, including the following: • Gilleland et al. 2013: *http://www.ral.ucar.edu/~ericg/softextreme.php* • WAFO: *http://www.maths.lth.se/matstat/wafo/documentation/wafotutor25.pdf.* • NEVA: *http://www.mathworks.com/matlabcentral/fileexchange/48238-nonstationary-extreme-value-analysis--neva--toolbox* • IHAMEVA: *http://ihameva.ihcantabria.com/introduccion/*				
2. Estimate Nearshore Hydrodynamics					
Analytical or semi-empirical approximations	Wave propagation	Large scales	Snell's law (that is, law of refrac-tion)	Approximates wave propagation for idealized geometries. Uses analytical solutions of linear wave theory for idealized bathymetry.	ECLAC 2012
	Storm surge propagation	Large scales	Dean and Dalrymple 1984	Step 1 with reference to storm surge also applies here.	

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Table 4.1: Coastal Engineering Models and Tools for Assessing Coastal Protection Benefits. *(continued)*

2. Estimate Nearshore Hydrodynamics					
Type of Approach	**Scope/Type of Problem**	**Scale of Applicability**	**Ex. of Models**	**Key Considerations**	**Ex. of Applications**
Numerical modeling	Wave propagation	Regional to local scales	*Spectral wave models:* Swan, STwave	Used for wave propagation in large domains, where the wave energy distribution is the main effect to consider.	Camus et al. 2011
		Local scales	*Mild slope based models:* REFDIF, CGWave, OLUCA	Provides accurate definition of near-shore processes at smaller domains: refraction, diffraction, and breaking.	UNEP 2011
	Storm surge propagation	All scales	SLOSH, ADCIRC, DELFT3D, CEST	Numerical models provide the best approach for computing the surge associated with tropical and extra-tropical storms. They generate the surge from the storm's meteorological conditions (wind and pressure) in 2D and 3D domains, with higher resolution closer to shore.	Zhang et al. 2012 Vatvani et al. 2012 Westerink et al. 2012

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Table 4.1: Coastal Engineering Models and Tools for Assessing Coastal Protection Benefits. *(continued)*

Type of Approach	Scope/Type of Problem	Scale of Applicability	Ex. of Models	Key Considerations	Ex. of Applications
3. Estimate the effect of coastal structures (habitat) on hydrodynamics					
A. MANGROVES					
Analytical or semi-empirical approximation	Wave dissipation from vegeta-tion	Large to regional scales	Dalrym-ple et al. 1984, Mendez and Losada 2004	Dissipation of waves based on vegetation parameters such as stem diameter, height, and density and relative submergence of plants.	Guannel et al. 2014
	Storm surge dissipation by vegetation[d]	Large to regional scales	—	Estimations of attenuation based on modeled studies or measurements.	For example, rules of thumb: Krauss et al. 2009– 9.4 cm/km Zhang et al. 2012– 40–50 cm/km across the mangrove forest
Numerical modeling	Wave dissipation from vegeta-tion	Regional to local domains	Swan-Veg, STWave, WHAF-IS(*1D*), IH2VOF (*1D*), —	Includes wave propagation models (*Step 2*) that incorporate wave dissipa-tion models by vegetation (Mendez and Losada 2004 or Dalrymple et al.1984).	Suzuki et al. 2011 Maza et al. 2013

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Table 4.1: Coastal Engineering Models and Tools for Assessing Coastal Protection Benefits. *(continued)*

3. Estimate the effect of coastal structures (habitat) on hydrodynamics					
B. CORAL REEFS					
Type of Approach	**Scope/Type of Problem**	**Scale of Applicability**	**Ex. of Models**	**Key Considerations**	**Ex. of Applications**
	Storm surge dissipation by vegetation[d]	Regional to local domains	ADCIRC SLOSH CEST	Includes storm surge models (*Steps 1 and 2*) for long wave propagation with different manning coefficients to account for the attenuation of the mangrove forest.	Zhang et al. 2012 Wamsley et al. 2010
Analytical or semi-empirical approximation	Wave transmission through the reef	All scales	Ahrens (1987) Van der Meer and d'Angremond (1991)	Includes transmission coefficient formulations for submerged breakwaters.[e, f]	
Numerical modeling	Wave transmission through the reef	Local domains	SWASH, FUNWAVE, IH2VOF	Wave breaking and dissipation induced by the structure. Some models account for the additional friction of the corals. Different options for models that vary in degree of complexity and accuracy.[g]	Buckley et al. 2014 Garcia et al. 2004 Lara et al. 2006

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Table 4.1: Coastal Engineering Models and Tools for Assessing Coastal Protection Benefits. *(continued)*

4. Estimate coastal protection metrics (Flooding & Erosion)					
A. COASTAL FLOODING					
Type of Approach	**Scope/Type of Problem**	**Scale of Applicability**	**Ex. of Models**	**Key Considerations**	**Ex. of Applications**
Analytical or semi-empirical Approximation	Wave run-up	All scales	beach run-up: Stockdon et al., 2006 rub-ble-mounds: Van der Meer and Stam (1992)	There are several semi-empirical formulations to estimate run-up statistics for the wave conditions and the geometry of the structures.	Stockton et al. 2012
Numerical modeling	Wave run-up & inland flooding	Small scales	SWASH FUNWAVE IH2VOF DELFT3D TUFLOW	Run-up over structures or beach profiles in 2DH, 2DV or full 3D.[h] Different options for models, varying in degrees of complexity and accuracy.[i]	Ruju et al. 2014 Buckley et al. 2014

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Table 4.1: Coastal Engineering Models and Tools for Assessing Coastal Protection Benefits. *(continued)*

4. Estimate coastal protection metrics (Flooding & Erosion)					
B. EROSION					
Type of Approach	**Scope/Type of Problem**	**Scale of Applicability**	**Ex. of Models**	**Key Considerations**	**Ex. of Applications**
Analytical or semi-empirical approximation	Cross-shore evaluation	Large to regional scales	Dean 1991 Soulsby 1997	Sediment movement on a beach profile.	UNEP 2011
	Long-shore evaluation of sediment transport	Large to regional scales	Bijkers 1971, Engelund and Hansen 1967, CERC 1984	Sediment movement along shore due to currents, oblique incidence of waves, and wave height gradients.	CERC 1991 Kamphius 1991

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Table 4.1: Coastal Engineering Models and Tools for Assessing Coastal Protection Benefits. *(continued)*

4. Estimate coastal protection metrics (Flooding & Erosion)					
A. COASTAL FLOODING					
Type of Approach	**Scope/Type of Problem**	**Scale of Applicability**	**Ex. of Models**	**Key Considerations**	**Ex. of Applications**
Numerical modeling	Cross-shore evaluation	Regional to small scales	MOPLA Delft3D, Xbeach	Sediment movement on a beach profile.	UNEP 2011
	Long-shore evaluation of sediment transport	Small scales	MOPLA Delft3D, Xbeach CMS	Coupled models and morphological models for sediment transport along shore in 2D or 3D.	Roelvink et al. 2009 Jamal et al. 2014 Eversole and Fletcher 2003

[a] Sources of wave data beyond numerical simulation include wave buoys (for example, http://www.ndbc.noaa.gov/) and satellite measurements, (for example, http://www.oceanor.com/Services/wwa_info/).
[b] Some examples of precomputed Wave Atlases: Global Ocean Waves: Reguero et al. 2012, 2013; NOAA: operational hindcast http://polar.ncep.noaa.gov/waves/index2.shtml and WW3 CFSRR Reanalysis Hindcasts http://polar.ncep.noaa.gov/waves/CFSR_hindcast.shtml.
[c] There are also some databases that provide measurements of storm surge for several locations, such as Surgedat: http://surge.srcc.lsu.edu/data.html.
[d] Surge attenuation depends strongly on the forest width and other factors, such as vegetation density and relative submergence or the storm velocity.
[e] Main parameters: structure geometry (crest width, slopes, freeboard) and porosity, incident wave parameters (height, period), and depth.
[f] It can be improved by: (1) Considering roughness of the reefs, and (2) Including the contribution from infragravitational waves through semi-empirical approximations.
[g] Options: Shallow water equation models, Boussinesq models, Navier-stokes models.
[h] 2DH refers to a two-dimensional domain in horizontal, while 2DV refers to vertical profiles (that is, a coastal transect).
[i] Options: Shallow water equation models, Boussinesq models, Navier-Stokes models.

A key result of this step is an assessment of both average and extreme offshore hydrodynamics conditions in the region of study. The key data in assessing these conditions are (i) historical records of past storm events, climatological and oceanic observation networks, (ii) observations and measurements (for example, satellite and wave gauges), and (iii) modeled climatic reconstructions (for example, NOAA National Climate Data Center[15]).

2. *Estimate nearshore hydrodynamics*

As soon as offshore waves approach and start to interact with the coastal environment, there is another set of processes that need to be studied with a different suite of tools. Waves change significantly throughout their propagation from deep to shallow waters because of interactions with the bathymetry and coastal geometry (although other factors like wind transfer can also affect the waves). In their propagation, waves experience refraction, dissipation, diffraction, and other sources of energy transfer.

A key result from this step is a characterization of nearshore wave heights and energy. These wave heights and energy are typically assessed across a range of average and extreme conditions (for example, see USACE 2002; ECA 2009). One of the key datasets to acquire at this stage is bathymetry. For regional- and global-scale analyses, the most common data sources are ETOPO[16] or GEBCO[17] (approximately 1 km resolution). These bathymetry datasets are adequate for large domains but cannot be used for local scale studies where shallow conditions are key for the relevant process, such as refraction and breaking. It is usually desirable to find more high-resolution bathymetry from nautical charts, surveys, or imagery (for example, Lidar) at local sites.

3. *Estimate the effects of coastal structures (habitat) on hydrodynamics*

Nearshore waves and surge then interact with habitats (or other structures), which results in wave attenuation and wave energy reduction. The models for estimating the effects of offshore structures (for example, reefs) and intertidal vegetation (for example, mangroves) are different. For instance, coral reefs attenuate short waves (for example, wind waves) mainly through wave breaking and wave energy dissipation, depending on relative depth, rugosity, and reef geometry (see Chapter 3). In contrast, mangrove forests can attenuate both short-wave energy and long waves (that is, storm surges) (see Chapter 2). Coral reefs can persist in high wave energy environments, while mangrove forests are found in areas more protected from intense wave action. The key result of this step is an evaluation of wave reduction resulting from the coastal habitats.

This step requires spatially explicit data on habitats. There is one relatively common set of global data on the distribution of coral reef and mangrove habitats that are available from several sources (see UNEP WCMC,[18] World Resources Reefs at Risk,[19] and Coastal Resilience[20]). In addition to estimating the distribution it is also important to estimate crest height (for example, using SeaWifs data[21]) and rugosity (see Sheppard et al. 2005) for reefs, and vegetation density

15 Some key databases include (i) storm events https://www.ncdc.noaa.gov/stormevents/; (ii) wave measurements http://www.ndbc.noaa.gov; (iii) tide levels http://www.oco.noaa.gov/tideGauges.html; and (iv) tropical cyclone tracks https://climatedataguide.ucar.edu/climate-data/ibtracs-tropical-cyclone-best-track-data. See Table 4.1.

16 http://www.ngdc.noaa.gov/mgg/global/global.html.

17 http://www.gebco.net/.

18 http://data.unep-wcmc.org/datasets/6.

19 http://www.wri.org/publication/reefs-risk-revisited.

20 http://maps.coastalresilience.org/global/.

21 http://oceancolor.gsfc.nasa.gov/SeaWiFS/.

for mangroves (for example, Mendez and Losada 2004; Satyanarayana et al. 2011; Tusinski and Verhagen 2014; Kamal et al. 2014). Some of the engineering models for estimating the effects of habitats on wave and surge are identified in Table 4.1.

4. *Estimate onshore flooding and erosion*

After passing over habitats, the remaining wave energy is translated into levels of onshore flooding or erosion. The models and equations for assessing erosion and flooding are different. **At present, most considerations of expected and averted damages focus on flooding impacts and rarely assess erosion.** This chapter briefly discusses how erosion can be estimated here, but primarily focuses on flooding impacts in step five. For flooding, a key result of this step is an assessment of onshore flooding levels relative to storm frequency (return periods).

4.1. Coastal flooding

Water levels along coastal shorelines vary through time. As a first order estimate, these water levels can be defined by (i) average sea level conditions, including mean water level, astronomical tides, storm surges, and wave setup, and (ii) fluctuating surf-beat from the individual waves at the shoreline, usually referred to as wave run up, that is, height above mean water elevation (USACE 2002). The run up is a very complex phenomenon that depends on the local water level, the incident wave conditions (height, period, steepness, and direction), and the nature of the structure (for example, slope, reflectivity, height, permeability, and roughness). All of these factors above determine the potential for flooding. Flooding can be modeled in a variety of ways depending on the scope and resolution needed for the study. As a first order estimate, a bathtub approach is usually taken where the flood height (total water level) at the shore is distributed across land based on topographic elevation creating a flooding envelope. More complex flooding models take into account different land uses (for example, different rugosity), duration of the events, or coastal defenses (for example, barriers and protections).

4.2. Coastal erosion

Coastal erosion is the wearing away of land and the removal of sediments by wave action, tidal currents, wave currents, and high winds. Wind waves may cause coastal erosion in the long term by provoking loss of sediment or the temporary redistribution of sediments (for example, under storm conditions). Erosion is usually studied by modeling both the cross-shore (that is, beach profile changes) and long-shore sediment transport (that is, beach platform variations). There are also methods to study the problem over short temporal scales and to consider the full three-dimensional complexity of the problem.

5. *Assess expected and averted damages (value coastal protection benefits)*

After flooding levels are modeled as a function of event frequency (for example, flood height versus storm return period), the next step is to assess the damages or losses from the events. The main analysis is a calculation of the people and assets within ("under") the flooding envelope (Figure 4.2). The expected damages can be adjusted by elevation with a **vulnerability curve** that characterizes past observed relationships between flood height and damage to structures. For example, a structure flooded by 0.5 meters of water will have less percent damage than a structure flooded by two meters of water (for example, Scawthorn et al. 2006a). The statistical relationship between these losses represents the *expected damage function*. This curve is a key result of these analyses and serves to define the likely value of assets flooded under different storm frequencies or return periods (for example, once in 10-, 100- and 500-year storms).

Spatially explicit data regarding the distribution of assets and economic activity is necessary to calculate the expected damage function (in particular by elevation). Spatially explicit information about property values are often available in high-income countries, but often not available in developing countries. In the absence of such data, one approach for assessing the distribution of coastal assets for large-scale studies is to spatially allocate national or subnational GDP based on population estimates, that is, translate exposed populations into exposed assets using an estimate of produced capital per capita (World Bank 2010; Hallegatte et al. 2011, 2013). GDP estimates are available from the World Bank and population estimates from several databases, including World Pop,[22]GRUMP,[23] or Landscan[24]. A dataset that already translates global gridded GDP by population into exposed assets is currently available from UNEP-Grid and the World Bank.[25] G-Econ[26] also provides geographically based economic data (Nordhaus 2005). Although it is less common, it is possible to allocate GDP based on the distribution of infrastructure from the global night-lights database (Henderson et al. 2011; Uchiyama and Mori 2015 discuss limitations in this approach).

Value coastal protection benefits. The final analysis in the assessment is the comparison of the expected damages function under alternative habitat conservation and restoration scenarios (for example, Reguero et al. 2014). For example, the restoration of mangroves or reefs will reduce flood heights across a variety of storm frequencies (return periods) compared to the base scenario, resulting in averted damages that can be estimated monetarily or in terms of the number of people affected. The difference in the expected damage curves with and without existing coastal habitats represents the current coastal protection benefit of the habitats (Figure 4.2). The value of these benefits can be calculated either (i) by comparing the difference in expected and averted damages at one or more specific storm return periods and/or (ii) by integrating the area between the curves (Figure 4.2), which represents the average annual averted damages (that is, the annual expected benefit from the habitats) (Olsen et al. 2015).

The approaches for estimating expected damages are common in the hazard management and insurance industry (Understanding Risk 2014). Risk models—such as Climada (see previous sections), CAPRA[27] (World Bank) or HAZUS[28] (Scawthorn et al. 2006b)—can inform the protection benefit calculations, while other tools can be used to estimate costs and benefits (for example, FEMA[29]; Climada).

Summary of coastal engineering tools and models

There are a wide range of tools and a rich history of practice for coastal protection modeling, because many different sectors need to study, understand, and control coastal erosion and flooding. Table 4.1 outlines some of the tools and models available for resolving the steps described above (models and tools briefly described in Appendices 1 and 2). Although the application of these approaches to reefs and wetlands is a more recent addition, there is nothing entirely new about incorporating natural structures in such models. Many of the

22 http://www.worldpop.org.uk.
23 http://sedac.ciesin.columbia.edu/data/collection/grump-v1.
24 http://web.ornl.gov/sci/landscan/.
25 http://preview.grid.unep.ch/index.php?preview=data&events=socec&evcat=1.
26 http://gecon.yale.edu/.
27 http://www.ecapra.org/.
28 https://www.fema.gov/hazus.
29 http://www.fema.gov/benefit-cost-analysis.

models within each step share commonalities, and all cited here are widely employed in coastal problem solving.

4.7| Summary and Advice

The approaches reviewed here can be applied across different scales for many ecosystems, including coral reefs and mangroves, with a variety of tools that vary in scope and level of accuracy. Importantly, the outputs of all approaches can be used for direct economic valuation (see Chapter 5). Defining the right approach for each case, however, is important for ensuring the most successful outcomes. Several considerations must be taken into account to determine which ecosystem service or coastal engineering tool or approach is best suited to estimate the role of natural habitats in coastal protection. Defining these factors can help users narrow the choices and better understand the differences in methodologies. Key considerations to identifying the appropriate approach are:

- **Purpose**—Can the tool address the problem and provide suitable outcomes for economic valuation? What is the available output?
- **Geographic scale and scope**—Is the analysis attempting to address coastal vulnerability at a national scale or at a specific study site?
- **Resolution of available information**—What data are already available or could be collected for the analysis? This data can range from meteo-oceanographic data (for example, wind-waves) to human assets values (for example, human population densities).
- **Technical resources**—What expertise and computing resources are available to set up and run the models or apply the tools?

Although most approaches for estimating and valuing coastal protection services require technical expertise, many of the general ecosystem service and coastal protection tools are becoming more accessible and easier to use. Given that the expertise is available to build them, numerous coastal engineering models and approaches can address the role of natural habitats in ecosystem services at a finer resolution. Many of the coastal engineering approaches reviewed here can readily address the role of coastal marine habitats in erosion and flood reduction, as well as to design restoration projects that maximize these benefits. However, transferring flood and erosion reduction into expected damage relationships needs to factor in the consequences on assets and human populations. The information, guidance, and processes described in this chapter can facilitate the inclusion of habitats in national accounts.

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Appendix 4.1: A Summary and Comparison of Ecosystem Service Tools and Approaches

MODEL	DESCRIPTION														CASE STUDIES
	Ease of Use					Input				Output			Cost		
	User-Friendly Interface	Open Source	Programming Skills Not Required	Well-documented Manual and Example(s)	Web-based or Stand Alone Application	Includes General Data	User Can Develop Scenarios	Ready to Use in Many Geographies	Does Not Require Data Gathering/ Parameterization to Start	Includes Benefit Estimates for Coastal Protection	Can Provide Cost Benefit Analysis	Provides Easy to Use Graphics	Free to Download	Does Not Require Specialized Training/ Partnership with Consultant	
COASTAL RISK AND VULNERABILITY TOOLS AND FRAMEWORKS															
Climada	—	✓	—	—	—	—	✓	—	—	✓	✓	✓	—	✓	U.S. Gulf Coast; Eight Caribbean Nations
CCP	—	—	—	✓	—	—	✓	✓	—	✓	✓	✓	—	—	Five Caribbean Nations
Coastal Resilience	✓	✓	✓	✓	✓	✓	✓	—	✓	✓	—	✓	✓	✓	Globally United States—Nationally & Regionally; Mesoamerican Reef, Grenada, St. Vincent
RiVamp	—	✓	—	✓	—	—	—	✓	—	✓	—	✓	—	—	Jamaica
GENERAL ECOSYSTEM SERVICE TOOLS—Multiple Ecosystem Services															
ARIES	✓	✓	✓	✓	✓	✓	✓	—	✓	✓	✓	✓	—	—	Madagascar; Washington; Latin America
InVEST	✓	✓	✓	✓	—	✓	✓	✓	—	✓	✓	✓	✓	✓	Texas; Belize; Hawaii; Oregon; Colombia; Vancouver Island
MIMES	✓	✓	—	—	—	—	✓	—	—	—	✓	—	—	—	Mass.; Cambodia; Texas

Tools were evaluated on the following characteristics:

- **Ease of use**—Modeling tools are technically advanced and have the ability to run custom analyses. They generally require some amount of technical expertise or training; however, as these tools become increasingly common, some are being developed with a nontechnical user in mind. The ease of use category includes the following: (i) the user-friendliness of the tool's interface; (ii) the ability for the public to access the tool's source code and modify its design, if desired (that is, is it open source?); (iii) whether the tool requires highly technical programming skills to get started; (iv) whether the tool is well-documented and explained in a user manual, peer-reviewed papers, or other publications (this can provide instructions as well as credibility to the tool); and (v) if the tool is either web-based or only requires one software application to run the model from start to finish.
- **Input**—This includes the following: (i) if the model provides general asset data, such as population densities; (ii) the ability of the user to model different scenarios, such as different levels of storm surge with and without coastal protection, or variations in sea level rise; (iii) if the model can readily be applied in a variety of regions (for the models that do not include general data, this requires that the user input data to start); and (iv) whether the user must collect and parameterize data to start setting up the model.
- **Output**—This category includes some discussion of what the tool can provide the user. This includes whether the tool provides the following: (i) ecosystem service values for the estimated benefits of coastal protection, such as by establishing the correlation between coral reefs or mangroves and beach erosion; (ii) cost benefit analysis; and (iii) graphic output that can be used easily to communicate the results with nontechnical stakeholders.
- **Cost**—Some tools require the purchase of software; others can be downloaded directly from the Internet for no charge. This category addresses whether (i) the tool is downloadable free of charge; and (ii) it can it be used without specialized training, working with the developer, or employing a qualified consultant to run the tool.

Appendix 4.2: Brief Description of Coastal Engineering Model and Tools

ADCIRC—(Luettich et al.1992) The ADvanced CIRCulation model (ADCIRC) is a two-dimensional, depth-integrated, barotropic time-dependent long wave, hydrodynamic circulation model. ADCIRC models can be applied to computational domains encompassing the deep ocean, continental shelves, coastal seas, and small-scale estuarine systems. Typical ADCIRC applications include modeling tides and wind driven circulation, analysis of hurricane storm surge and flooding, dredging feasibility and material disposal studies, larval transport studies, and near shore marine operations.

http://adcirc.org/.

CEST—(Xiao et al. 2006) The Coastal and Estuarine Storm Tide (CEST) model is a three dimensional, finite difference model developed by the International Hurricane Research Center (Florida International University, Miami, Florida) to simulate estuarine and coastal flooding induced by hurricanes. The CEST model is forced by winds, atmospheric pressures, and astronomical tides or a time series of water levels at open boundaries. It is capable of simulating storm tides, as well as the wind-driven circulation at estuaries and coasts. The model can also include river flow in the simulation.

http://www.myroms.org/.

CGWAVE—CGWAVE is a general-purpose wave prediction model for simulating the propagation and transformation of ocean waves in coastal regions and harbors, and appropriate for modeling the most significant physical processes in channels, inlets and harbors, open coastal regions, and around islands and structures.

http://www.aquaveo.com/software/sms-cgwave.
http://chl.erdc.usace.army.mil/chl.aspx?p=s&a=software;21.

CMS—The CMS consists of a flow model (CMS-Flow) and a wave model (CMS-Wave). CMS-Flow is a two dimensional depth-integrated model for simulating wave-averaged hydrodynamics and nonuniform sediment transport and morphology change in coastal waters. CMS-Flow calculates currents and water levels and includes physical processes, such as wetting and drying, advection, wave-enhanced turbulent mixing and bottom friction, forcing from wind, atmospheric pressure, waves, river, tides, and the Coriolis-Stokes force. CMS-Wave is a two dimensional, finite-difference spectral wave model and simulates wave generation, transformation, and dissipation. Physical processes calculated in the model include refraction, diffraction, reflection, bottom friction, breaking, waves-current interaction, and structure effects. CMS-Flow and CMS-Wave are tightly coupled and may be run on the identical or varying computational grids. The models also support grid nesting within larger domain simulations. CMS is interfaced through the Surface-water Modeling System (SMS).

DELFT3D—Delft3D is a flexible integrated modeling suite that simulates two-dimensional (that is, horizontal or vertical planes) and three-dimensional flow, sediment transport and morphology, waves, water quality and ecology and is capable of handling the interactions between these processes. The suite is designed for use by domain experts and nonexperts alike, which may range from consultants and engineers or contractors, to regulators and government officials, all of whom are active in one or more of the stages of the design, implementation, and management cycle.

http://www.deltaressystems.com/hydro/product/621497/delft3d-suite.

FUNWAVE —(Wei et al. 1995) FUNWAVE is a phase-resolving, time-stepping Boussinesq model for ocean surface wave propagation in the nearshore.

http://chinacat.coastal.udel.edu/programs/funwave/funwave.html.

IH2VOF—(Lara et al. 2006) **IH2VOF** solves the two-dimensional wave flow for waves and permeable and impermeable structures, outside and inside the porous media, by resolving the Volume-Averaged Reynolds Averaged Navier-Stokes (VARANS) equations. Turbulence is modeled using a k-ε model for both the clear-fluid region and the porous media region.

http://ih2vof.ihcantabria.com/.

OLUCA—(Gonzalez et al. 2007) A weakly nonlinear combined refraction and diffraction model, which simulates the behavior of monochromatic waves (Oluca-mc version) and a random sea (Oluca-sp version), over irregular bottom bathymetry. These models include the effect of shoaling, refraction, energy dissipation (bottom friction and wave breaking), diffraction, and wave–current interaction. It can be found in the MOPLA suite.

MOPLA—(Gonzalez et al. 2007) Software that integrates a series of numerical models for the implementation of a coastal research and design methodology and the analysis of coastal morphodynamics: wave propagation, currents, sediment transport, and so on.

http://www.ihcantabria.com/en/servicios/puertos-infraestructuras/item/392.

REFDIF—(Kirby and Dalrymple1983) REF/DIF is a phase-resolving parabolic refraction-diffraction model for ocean surface wave propagation.

http://chinacat.coastal.udel.edu/programs/refdif/refdif.html.

ROMS—Regional Ocean Modeling System (ROMS) is a free-surface, terrain-following, primitive equation ocean model widely used by the scientific community for a diverse range of applications. The model is developed and supported by researchers at the Rutgers University, University of California, Los Angeles and contributors worldwide

S-Beach—(Larson and Kraus 1989) The Storm-induced BEAch CHange model (SBEACH) is a numerical simulation model of cross-shore beach, berm, and dune erosion produced by storm waves and water levels. The model is applied in beach fill project design and evaluation and in other studies of beach profile change.

http://www.veritechinc.com/products/cedas/sbeach.php.
http://chl.erdc.usace.army.mil/chl.aspx?p=s&a=Software!31.

SLOSH—(Jarvinen et al. 1985) The Sea, Lake and Overland Surges from Hurricanes (SLOSH) model is a computerized numerical model developed by the National Weather Service (NWS) to estimate storm surge heights resulting from historical, hypothetical, or predicted hurricanes by taking into account the atmospheric pressure, size, forward speed, and track data. These parameters are used to create a model of the wind field, which drives the storm surge. The SLOSH model consists of a set of physics equations, which are applied to a specific locale's shoreline, incorporating the unique bay and river configurations, water depths, bridges, roads, levees, and other physical features.

http://www.nhc.noaa.gov/surge/slosh.php.

SWAN—(Booij et al. 1999) SWAN is a third-generation wave model that computes random, short-crested wind-generated waves in coastal regions and inland waters. SWAN computations can be made on a regular, a curvilinear grid, and a triangular mesh in a Cartesian or spherical coordinate system.
http://swanmodel.sourceforge.net/.
http://chl.erdc.usace.army.mil/chl.aspx?p=s&a=software;9 http://www.aquaveo.com/.software/sms-stwave.

SWAN-Veg—(Suzuki et al. 2011) SWAN has an option to include wave damping over a vegetation field (mangroves, salt marshes, and so one) at variable depths.

http://swanmodel.sourceforge.net/online_doc/swantech/node21.html.

SWASH—(Zijlema et al. 2011) SWASH is a general-purpose numerical tool for simulating unsteady, nonhydrostatic, free-surface, rotational flow, and transport phenomena in coastal waters as driven by waves, tides, buoyancy, and wind forces. It provides a general basis for describing wave transformations from deep water to a beach, port or harbor, complex changes to rapidly varied flows, and density driven flows in coastal seas, estuaries, lakes, and rivers.

http://swash.sourceforge.net/

TUFLOW—Tuflow provides one-dimensional and two-dimensional solutions of the free-surface flow equations to simulate flood and tidal wave propagation. It can be applied where the hydrodynamic behavior in coastal waters, estuaries, rivers, floodplains, and urban drainage environments have complex two-dimensional solutions flow patterns that would be awkward to represent using other one-dimensional network models.

http://www.aquaveo.com/software/sms-tuflow

WAM—(WAMDIG 1988; Komen et al. 1994) The global ocean WAve prediction Model called WAM is a third-generation wave model. WAM predicts directional spectra, as well as such wave properties as significant wave height, mean wave direction and frequency, swell wave height and mean direction, and wind stress fields corrected by including the wave induced stress and the drag coefficient at each grid point at chosen output times.

http://chl.erdc.usace.army.mil/chl.aspx?p=s&a=software;8

WW3 or **WaveWatch III**—(Tolman 2002, 2014) is a third generation wave model developed at NOAA/National Centers for Environmental Prediction (NCEP) in the spirit of the WAM model. WAVEWATCH III® solves the random phase spectral action density balance equation for wave number-direction spectra. The implicit assumption of this equation is that properties of medium (water depth and current), as well as the wave field itself, vary on time and space scales that are much larger than the variation scales of a single wave. Last versions include surf-zone physics, but they are still rudimentary.

http://polar.ncep.noaa.gov/waves/wavewatch/

WHAFFIS —Wave Height Analysis for Flood Insurance Studies (WHAFIS), Version 4.0, is a DOS-based program that uses representative transects to compute wave crest elevations in a given study area. Transects are selected by considering major topographic, vegetative, and cultural features. WHAFIS uses this and other input information to compute an appropriate depth-limited wave height at the seaward end of each transect.

http://www.fema.gov/national-flood-insurance-program-flood-hazard-mapping/wave-height-analysis-flood-insurance-studies

XBeach—(Roelvink et al. 2009; Van Thiel de Vries 2009) XBeach is a two-dimensional model for wave propagation, long waves and mean flow, sediment transport, and morphological changes of the nearshore area, beaches, dunes, and back barrier during storms. It is a public-domain model that has been developed with funding and support by the U.S. Army Corps of Engineers, by a consortium of UNESCO-IHE, Deltares (Delft Hydraulics), Delft University of Technology, and the University of Miami.

http://oss.deltares.nl/web/xbeach/home

5| Approaches for Valuing Coastal Protection Services in a Natural Capital Accounting Framework

Jim Sanchirico,[e,f] Juha Siikamaki,[f] Glenn-Marie Lange,[g] and Anne Riddle[e]

5.1| Summary

Previous chapters have discussed the biophysical aspects of coastal protection, but a full accounting for these services and the assets providing them requires estimating the economic value as well. The economics profession has developed a large suite of tools for valuing ecosystem services that are not typically traded in markets and, thus, do not have readily observable prices. This section opens with a discussion of the different types of ecosystem services and methods developed to estimate their values with special attention to those tools used to value the protective services of coral reefs and mangroves. This guidance note aims to explore how these values might be linked to national economic accounts. This is important, because national accounts, providing such indicators as GDP, are the primary way that national economic performance is monitored and a major input into policy analysis. The System of Environmental Economic Accounting (SEEA; European Commission et al. 2012) is a satellite account to the System of National Accounts (SNA; European Commission et al. 2008) developed to better represent the role of natural capital in the economy. By incorporating natural capital explicitly in the SEEA, linked to national economic accounts, the economic importance of natural capital can be more readily recognized by mainstream economists and mainstreamed into decision making. The chapter concludes with recommendations on an approach to valuation for coastal protection services in the SEEA framework, aligned with the SNA.

The existing literature on the value of coastal protective services is limited both by the number of studies and their geographic coverage. Most valuation studies come from South East Asia, but other world regions where mangroves and coral reefs are prevalent are also represented in the literature. The most commonly used valuation method is the replacement cost method for assessing the comparative value of the protection provided by mangroves and coral reefs (for example, as compared to the cost of building alternative protection, such as sea walls). However, this approach provides valid estimates of economic value only under highly restrictive criteria and its prevalence in the economic literature is largely because of the ease of application.

For coastal protection services, production function methods, especially the EDF approach, provide more valid estimates of economic value and are also aligned with concepts of the SEEA and SNA. The EDF approach builds from engineering and insurance-based models for estimating the property protection value (or avoided damages) of coastal structures (see Section 4).

The effort to extend the national accounts to include natural capital resulted in the adoption by the UN Statistical Commission of the System of Environmental Economic Accounting-Central Framework (SEEA-CF) as an international statistical standard in 2012, which nearly all countries have implemented to measure economic performance. The SEEA-CF is linked to the SNA by common concepts, methods and classifications; it extends the SNA to include stock and flow accounts for land, material resources, energy, emission of pollutants and monetary accounts for environmentally related taxes, and subsidies, as well as revised macroeconomic aggregates and

[e] University of California, Davis.
[f] Resources for the Futur.
[g] World Bank.

indicators, such as GDP. In this way, the SEEA-CF includes many of what the Millennium Ecosystem Assessment (2005) called the provisioning services of ecosystems, although it does not use that term directly. But the SEEA-CF does not address the regulating ecosystem services. The SEEA Experimental Ecosystem Accounts (UN et al., 2013) was developed to take a broader approach to ecosystem accounting and presents the best practice in ecosystem accounting so far, but this is a very new field, and the handbook is intended as a guide for experimentation and learning, rather than an agreed accounting framework.

While there has been important progress in developing and implementing accounting systems, considerable challenges remain. Many regulating services have value because they are inputs to economic production, but without a market price, these inputs are not identified in the national accounts and their value attributed to the using sector. For example, pollination services provided from a forest or wetland is captured in the value of agricultural output in the national accounts. Ecosystem accounts are intended to make explicit the contribution of this nonmarket service in order to improve economic management. Coastal protection is also a type of nonmarket intermediate service that contributes to the value of infrastructure, housing and other assets, and in a well-functioning property market, the price of these assets would reflect the protection service. But it is not clear whether this value is currently comprehensively included in the market price of housing and other assets; often this data may be difficult to obtain in developing countries.

Overall, there is a deep understanding of the biophysical features of protective services, but the level of experience and knowledge on the economic valuation of protective services of mangroves and coral reefs is thin. The development and greater use of biophysical models to assess the role of mangroves and coral reefs in preventing flooding and erosion, described in earlier chapters, could provide a more systematic and consistent method to assess benefits of protective services; additional research on estimating the magnitude of economic benefits associated with protective services is warranted to guide decision makers about where to prioritize investments in natural assets, either on their own or in combination with built infrastructure.

5.2| Introduction

During the past 15 years, there has been growing interest in the quantification of the economic values associated with ecosystem services (for example, Daily 1997; Heal 2000; Bockstael et al. 2000). The basis for this interest stems from two distinct but related areas of inquiry. First, there is the concern that by not valuing these resources explicitly, decision makers are implicitly assigning a value of zero on them in project level assessments (Bateman et al. 2013; Sanchirico and Springborn 2011). The implication of a zero value in a cost-benefit analysis, for example, is that project level activities that degrade ecosystem functions are favored over those that maintain or restore the functions that produce the ecosystem services (for example, Bateman et al. 2013). Second, there is a small, but growing, body of literature on how to incorporate ecosystem services into national accounts based on the SEEA-EEA and other approaches (for example, Edens and Hein 2013). The main motivation is similar to those for the project level analysis. That is, by including ecosystem services, national accounts will better illustrate the role that ecosystem assets and services play in the economic activity of a country, and will provide a tool for incorporating natural capital in development planning.

This chapter discusses the available methods to value the coastal protective services provided by coral reefs and mangroves. It then considers how well these approaches align with the SNA and SEEA framework that has been developed to incorporate ecosystems, including the assets (for example, forests), and the flows from those assets (for example, timber). One important distinction between valuation exercises for projects and valuation for national accounting is that the latter requires that the values be as close to exchange values as possible (values expressed through transactions or potential transactions), while the former is focused on measuring the welfare gains of a particular project (that is, willingness to pay, consumer surplus). A more detailed discussion of valuation concepts in national accounts and nonmarket services can be found in Nordhaus (2006), Obst et al. (2015), and World Bank (forthcoming 2016).

The Ecosystem Services Valuation section provides background on the methods to value different types of ecosystem services and reviews the existing valuation literature. The section "Ecosystem Services and Natural Capital Accounting" provides background on the SEEA, with particular focus on the SEEA Experimental Ecosystem Accounts (SEEA-EEA) and on the challenges of incorporating coastal protection services into the SEEA-EEA framework. Finally, there is a discussion of the findings and recommendations for incorporating the value of ecosystem assets and services into SEEA accounting framework.

5.3| Ecosystem Services Valuation

This section briefly defines the concept of ecosystem services, discusses economic values associated with ecosystem services, reviews different approaches for estimating the value of ecosystem services, and discusses applications for measuring coastal protection benefits from reefs and wetlands.

Ecosystem services and their value

Ecosystem services fall into four categories: provisioning, regulating, supporting, and cultural (Millennium Ecosystem Assessment 2005). Provisioning services are embodied in the products that are directly consumed, such as the fish produced by a fishery or a crop from agricultural land. These services are most often traded in markets. Supporting services are underlying ecosystem processes, such as soil formation and oxygen production, which support the functioning of other ecosystem services. Regulating services are ecosystem functions that control biophysical cycles and levels, such as nutrient cycling, water filtration, or flood frequency and height (Millennium Ecosystem Assessment 2005). Coastal protection from mangroves and coral reefs, through erosion reduction or flood mitigation, is a regulating service, while the fish production from coral reef and mangrove habitats is a provisioning service. Finally, cultural services are the intangible benefits ecosystems provide to people through emotional enjoyment, such as aesthetic experiences and recreation.

For the purpose of valuation, a distinction is made between the provision of services and the benefits humans derive from the service. Only those services that benefit humans are considered to have economic value. Values associated with ecosystem services are often categorized by economists as "use or nonuse," "direct or indirect," and "market and nonmarket." Use values encompass goods and services that can be tangibly used either directly or indirectly (EPA 2008). Goods or services used directly—for example, fish harvested from a mangrove—are a direct-use good. Indirect uses comprise goods and services that are not used directly, but still provide use-benefits of economic value (EPA 2008). For example, flood control and wave energy attenuation from mangroves and coral reefs are an indirect-use value as they contribute a valuable input into the other economic goods and services, such as housing. Typically, indirect services do not have market prices, but the housing market may provide useful information to examine the values associated with such services, as explained below in the discussion of ecosystem service valuation methods. Nonuse values comprise ecological goods and services that are not physically used but still hold economic value (EPA 2008). Existence values, wherein individuals value the knowledge that certain ecosystems exist and will continue to exist, are examples of nonuse values.

Ecosystems often simultaneously contribute toward many types of services and values (see Cesar and Chong [2004] and Farber et al. [2002]). For example, the same tidal marsh may provide the direct-use values of oyster production for fishers and recreation opportunities for birders, the indirect-use value of erosion regulation for adjacent communities, and the existence value individuals place on the bay ecosystem.

Valuation methods for mangrove and coral reef ecosystem services

This section gives a brief description of the methods to value ecosystem services (see Appendix 5.1 for a list of the methods). Discussing the technical issues associated with each method is beyond the scope of this report. Interested readers should consult Freeman (2003) and Holland et al. (2010). The section then discusses results of an extensive literature review on the estimates and methods used in prior research.

Market valuation

Most provisioning ecosystem services are often exchanged in markets and market prices are used to value them. Market information can also be used to measure goods and services for which a market price is not directly observable. For example, the SNA includes the value of goods that are not exchanged in markets, but potentially could be, such as fish harvested by a household for its own consumption. Typically, the fish used for own consumption is valued at the price of similar fish exchanged in markets.

However, many ecosystem services are not exchanged in markets so they lack the information, such as prices, to assist valuation. Nonetheless, there are methods for valuation of nonmarket goods. They are typically divided into revealed preference methods, where the value of the ecosystem service is revealed through the behavior of economic actors, or stated preference methods, where the value is directly elicited by statements made by individuals in a hypothetical setting. This section reviews the primary methods that are relevant to valuing coastal protection. Other valuation techniques that are not relevant will not be reviewed here. These include, for example, the travel cost method, which is mainly used to estimate recreation services.

Revealed preference methods for coastal protection

Hedonic price studies can be used to estimate indirect use values for ecosystem services that affect the prices of marketed goods. The hedonic method rests on the notion that the price of a marketed good reflects all of the attributes of the good (Freeman 2003). Most typically, it is applied to property values, where variations in price reflect the characteristics of the house (for example, number of bedrooms or bathrooms) and also the value of local public goods. The local public goods include quality of the schools, safety (police and fire), public infrastructure (roads), and environmental amenities (such as views, proximity to aesthetically desirable ecosystems, such as waterways, or mature vegetation) or environmental quality (such as air and water pollution) (Freeman 2003).

To measure how much individuals value a single environmental attribute, such as distance to the coast, one controls for all other attributes of the property's price. The remaining systematic variation in relation to distance to the coast reflects the individuals' value for coastal proximity of the property. The range of ecosystem services that can be measured with this technique is limited to benefits related to housing prices (and therefore, to specific locations), and to those ecosystem services wherein individuals perceive the benefit and link it to the property they buy (Landrey 2011). In one study, Landrey, Keeler, and Kriesel (2003) find that a one meter increase in beach width adds $233 to property values (at the mean of their data), where beach width increases the recreational experience and yields improved protection from coastal storms (see also studies by Pompe [2008] and Pompe and Rinehard [1995]). In principle, hedonic analysis can be used to value coastal protection services should those services shelter property that is subject to transactions. A key challenge is to carefully control for other aspects of the property's value in order to isolate the value of the protective service. This approach may be difficult to implement in developing countries, because it relies on extensive data on either actual market transactions or appraised values, which are often not available.

Averting behavior methods use costs incurred by individuals attempting to avoid or mitigate the effects of poor environmental quality. For example, consumers may respond to poor quality tap water by buying bottled water or installing filters, incurring additional costs. The value for improving the tap water quality can then be imputed from the consumers' expenditures (Abdalla et al. 1992). In terms of coastal protection, a homeowner paying to raise the foundation of a house is a form of averting behavior with the goal to avoid the costs of damage from flooding events.

The replacement cost method estimates the cost of providing a service of interest should the ecosystem no longer function properly or no longer exist. Typically, it involves estimating the cost of a seawall or other engineering structure to replace coastal protection provided by mangroves. This approach has been widely used for the valuation of coastal protection services, because there has been extensive experience with engineering structures so that the costs are well known, making implementation of this approach relatively easy. However, replacement cost is unlikely to coincide with the marginal willingness to pay for this service, making it less useful for accounting purposes. Replacement cost methods are only valid measures of the economic value of the service under rather stringent criteria: (i) if the same service is supplied by the ecosystem and the alternative provider; (ii) if the replacement alternative is the least cost replacement option, and (iii) if the replacement alternative would actually be implemented, if unavailable from the ecosystem (Boyer 2004; US EPA 2009). Replacement cost methods should also only be used to measure one service at a time, which is consistent with valuing flood and storm surge protection.

Vincent (2015) has suggested that replacement cost could be used in combination with contingent valuation (discussed below) in which contingent valuation is used to estimate willingness to pay for the service. If the willingness to pay is at least as great as the cost-based measure, then replacement cost can be used, meeting the criteria cited above.

More generally, coastal protective services are potentially substitutable with engineering solutions, such as seawalls or breakwaters, depending on the scale of the project under consideration. For example, if the decision is whether to clear a hectare of mangroves, then it is likely that a breakwater at that scale (or at least the scale necessary to provide the same level of protection) is technologically feasible. If the scale is tens or hundreds of hectares of mangroves (for example, at the scale of a country's stock), then it is not technologically feasible to employ an equivalent technology. In this case, replacement cost is not an appropriate method of valuation. Thus, depending on the analysis and questions asked in the valuation exercise, it is possible that the replacement costs are a viable measure of the economic value of coastal protective services.

In situations where payments for ecosystem services (PES) markets exist in a competitive form, these prices directly reflect market transactions and are also potentially applicable for the service in question (UN et al. 2014). Other examples of ecosystem service exchange values include access permits, tourism expenditures, land value, insurance premiums, and remediation costs (ABS 2015). However, in the majority of cases, the payments are a poor proxy for the economic value of ecosystem services provided. The payments are most often fixed payments, not set in competitive markets and thus unlikely to reflect the actual value of the service. After many years of experience with PES, there is increasing interest in assessing the extent to which the payments reflect the actual value. As more work is done on this subject, it will become clearer when PES is a reasonable proxy for value.

Stated preference methods

Personal preferences for nature and ecosystems are often based on more than their worth in use. Such nonuse values are difficult to measure, because they are not captured in market transactions or other observable actions, such as recreation site choice. This problem has given rise to the development of a variety of nonmarket valuation methods that use surveys to elicit preferences for public goods. Because these methods are generally based on eliciting "stated" rather than "revealed" preferences, they are broadly categorized as stated preference (SP) methods (Krupnick and Siikamäki 2007).

SP methods use surveys designed to elicit respondents' Willingness to Pay (WTP) for improvements or protections to a specified environmental resource, such as the extent and quality of habitat, species protected, or the quality of air or water resources. Contingent valuation and choice experiment are the two primary methods for SP analysis. In a typical contingent valuation survey, each respondent is asked, often using a voting question, to approve or disapprove the proposed environmental scenario given its monetary cost. Researchers vary the program costs across different survey respondents and use their choices to estimate how much people are willing to pay for different scenarios to improve the environment (Mitchell and Carson 1989; Freeman 2003; Krupnick and Siikamäki 2007).

In a choice experiment, respondents identify their preferences among one or more programs or alternative management strategies specifically altering different attributes of the program, such as its different environmental outcomes and monetary cost. By varying the levels of these attributes (including cost) across different scenarios and by examining respondents' choices, it is possible to estimate how much people are willing to pay for the different attributes of the program, as well as the entire program (Freeman 2003).

These approaches have been used most often to estimate such nonuse values as recreational services and wildlife preservation, and have also been used to estimate public willingness to pay for new public drinking water sources (Johnston 2006). This approach has not been used to value coastal protection services.

Because SP methods do not use information revealed by actual choices, their validity in estimating the true WTP is challenged (Murphy et al. 2005). More problematic, stated preference methods include consumer surplus so the values produced are not consistent with the exchange value concept of the SNA and cannot be used in the SEEA/EEA directly. It is possible to derive an estimated exchange value from stated preference studies by tracing a demand schedule that is combined with an estimation of a supply curve (Edens and Hein 2013; UN et al. 2014). Undertaking such an exercise can be done using the simulated exchange method as discussed in Siikamaki and Layton (2005) and Oviedo et al. (2010).

Production function methods and the Expected Damage Function

Production function (or bioeconomic) models are commonly used to measure services that provide indirect input to something that society values, such as the water supply and sediment control services of forests to hydroelectricity. Production functions describe the manner in which an output is related to the quantity and nature of inputs used to create it. An ecosystem's structure, such as size, vegetation, boundaries, and its functional aspects, such as ability to absorb floodwater or remove contaminants from surface water, are biophysical contributors—as inputs—to the services the habitat generates. These biophysical attributes for estimating coastal protection services for mangroves and reefs are well known and the previous chapters have described a production function approach to measuring coastal protection.

The Expected Damage Function (EDF) approach presumes that the value of an asset that reduces the severity or probability of economic damage, such as coastal mangroves or coral reefs, can be measured by the reduction in the expected damage. This method is an extension to production function methods, applicable for valuing regulating services, which by definition, protect nearby economic activities from possible damages (Barbier 2007). The engineering and insurance sectors have used EDF as a general approach to assess the cost effectiveness of alternatives for flood and erosion risk reduction (see Chapter 4 for further description of the EDF approach, and the data required and available to measure it).

To illustrate how EDF yields economic measures of value, consider, for example, a coastal community where homes, businesses, and public infrastructure are threatened by damage from periodic storms. If the expected incidence of storm damage rises, say from the loss of coastal mangroves, then households subject to the risks require greater income to reach the same level of wellbeing they had prior to the change in storm incidence. The presence of coastal wetlands mitigates the expected incidence of storm damage and thus, provides a benefit similar to an increase in income. Conversely, a loss in wetland area would increase expected storm damages and be equivalent to a loss of income. This change in income, also known as compensating surplus, provides the theoretical rigor to EDF as a measure of economic value.

A limitation of the EDF approach is that it values expected damages, rather than people's valuation of the risk. That is, the EDF approach assumes that people are indifferent to risk. However, people tend to be risk averse and prefer certainty over riskiness. For example, coastal households likely want to not just experience fewer damages from storms, but also a smaller variances in expected storm damages (that is, they would rather storms be not only small, but also consistent in the damages caused each time). This suggests there should also be a "risk premium" in addition to the storm protection value, which measures how much the ecosystem reduces the variance in expected damage from storm events (Barbier 2007; Hirshleifer and Riley 1992).

Implementing valuation methods and benefit transfer

The data required for directly implementing the valuation techniques were described above. In some cases, an alternative approach to directly implementing these techniques is used, called benefit transfer. The basic principle of the benefit transfer method is to value ecosystem services in one location by drawing from information on their value in another location. The method, therefore, involves a geographic transfer of valuation results. There are three main approaches to benefit transfer: value transfers; benefit function transfers; and meta-regression transfers. A value transfer directly applies an estimate of the value of an ecosystem service to another. A benefit function transfer takes an estimated function, which describes how the ecosystem service is related to the value estimated, and applies it from its original context to another. The most comprehensive method is a meta-regression analysis, which uses all relevant existing studies and estimates a function to predict the value of ecosystem services as a product of site characteristics, size, and attributes of the affected human population.

A typical challenge with this method is that the original information imperfectly or poorly matches the biophysical and socioeconomic conditions in the target area of the transfer. The value of ecosystem services depends on the biophysical, economic, and institutional context. Furthermore, ecosystems are interdependent: the value of an ecosystem service likely depends on the existence or location of other ecosystem components. Therefore, assuming that the valuation results from one ecosystem will be directly applicable to another can be problematic.

For valuing protective services, location-dependent drivers of the value are likely considerable, so any attempt to use a benefit transfer approach should incorporate them. For example, the value of protective services will necessarily depend on the value of local property, subject to the risk of coastal flooding, as well as the likelihood of storms and flooding in the local setting.

Valuation literature on coastal protective services

This section reviews and discusses current literature on the economic valuation of ecosystems services from mangroves and coral reefs for coastal protective services (for example, meta-analysis of values for coral reefs [Brander et al. 2007] and for mangroves [Brander et al. 2012]). A literature review was done to examine coastal protection and many other ecosystem services. There were 175 studies and 477 associated value estimates addressing different ecosystem services from corals and mangroves. About 52 percent (248) of the value estimates address coral reefs. Mangroves are the subject of valuation in 45 percent (214) of estimates. A small minority (3 percent) of value estimates address multiple ecosystems.

Value estimates in the database represent a wide range of different types of ecosystem services. Recreation is the ecosystem service addressed by the largest number of value estimates, with about 29 percent (129) of the value estimates (Ghermandi and Nunes 2013). The second and third largest ecosystem services types are fisheries (74 estimates; 16 percent of all value estimates) and the provision of raw materials (51 estimates; 11 of all value estimates).

Studies to value ecological protective services are the fourth most common in the database. For example, 34 value estimates address protection from flooding. Erosion is addressed by seven estimates and the valuation of coastal protection specifically is the purpose of five estimates. Altogether 46 value estimates are associated with protective services.

Of the 46 value estimates for protective services, most were in Southeast Asia (18 estimates), followed by the Caribbean and South Asia (Figure 5.1). Therefore, although many regions are represented in the data, the amount of information per region is limited. An implication of the spatial distribution is that a researcher conducting a benefits transfer would need to consider the applicability of estimates, for example, from Southeast Asia for the Caribbean.

Appendix 5.2 summarizes the studies that focus on coastal protection, including information on the services valued, the unit of the valuation (endpoint), method of estimating value, and the method used to estimate physical damages. About one third of the value studies use the replacement cost method (Figure 5.2 and Appendix 5.2). Other key valuation methods include the avoided cost method (11 estimates) and direct market pricing (eight estimates). The endpoints measured in each study vary but are often in dollars per distance squared measured annually. However, there are studies that convert the expected annual loss into a net present value over a period of time by discounting the loss out into the future (Spurgeon 2003).

The distance measure varies where some authors consider the elevation within which the flooding will occur, while others use a simple cut-off of distance from the coast without regard for elevation. The decision on how to determine the extent of the damages to consider and value is

Figure 5.1: Value Estimates for Protective Services by World Region

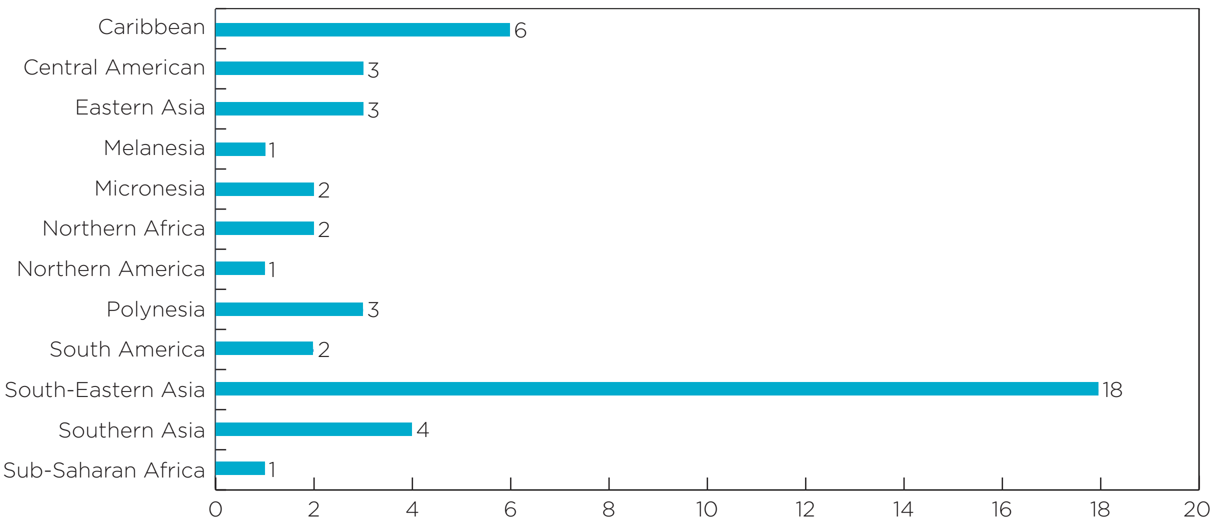
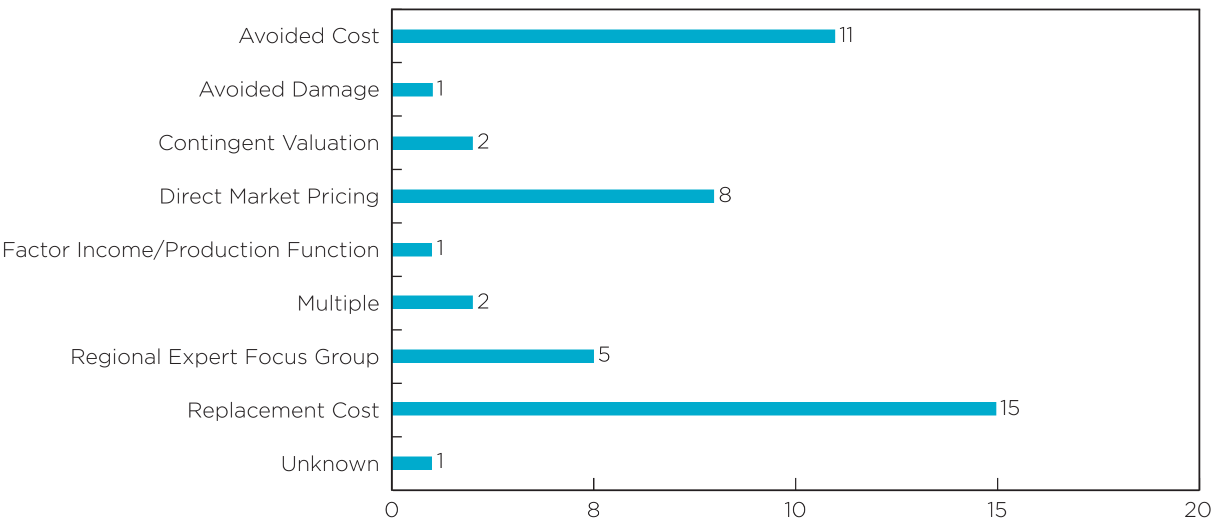


Figure 5.2: Value Estimates for Protective Services, by Valuation Method



context specific (see Chapter 4), but authors often use rules of thumb, flat rates (that is, 5 percent of all property value will be lost), or some combination of the two. Some studies do not measure damages, but consider the value of coastal property. Many studies use cost-based methods but do not discuss whether the conditions for using the methods are met in the current context.

While the endpoints are generally at a fine spatial resolution, the estimated values do not consider interactions across the impacted domains. For example, the construction material (such as concrete) and height of buildings (one versus two story) will influence the expected damages. Other factors that are often omitted include the orientation of the town relative to the shape of the coast and the main channel of storm surge. Furthermore, values are often somewhat crudely downscaled from larger scale aggregate value, such as the estimated value of property in a broader region—dividing the aggregate value by the size of the target area to develop a finer scale estimate, for example (see column labeled "conversion" in Appendix 5.2). The use of aggregate values is a common issue in the ecological valuation literature.

In the natural resource economics literature, the EDF approach was first applied to the economic valuation of coastal protection services provided by coastal wetlands in Farber (1987). More recently, Barbier (2007, 2014) has further developed the EDF approach for coastal protection services and compared it to replacement cost methods. Using data from Thailand and their estimated costs of breakwater construction ($1,011 per meter of coastline), he estimated the replacement cost of a similar amount of mangroves to be $13.48 per square hectare. Given the rates of mangrove loss in Thailand, he estimated the net present value of welfare loss over a 20-year period at $23 to $28 million. In contrast, using the EDF approach and considering past storm damages in Thailand, he estimated the net present welfare loss in storm protection was $3.1 to $3.7 million. The difference between the replacement cost approach and EDF was nearly an order of magnitude. Barbier (2007) argues that relative to the replacement cost method, the EDF approach provides a more robust measure of the value of coastal protective services, especially for large-scale assessments. This application of the EDF approach did have limitations in that the effectiveness of mangroves in reducing storm damage was inferred from past events.

More recently, Barbier (2014, 2015) carried out studies applying the EDF approach to coastal protection services in the Gulf of Mexico, following Hurricane Katrina. Coastal marshes, rather than mangroves or coral reefs, provide ecological protection in this study area, but the application of the EDF approach to coastal protection is the same.

In sum, there exists a large suite of tested approaches for ecosystem service valuation. Each method is suited for some ecosystem services and each requires different types of data and data collection methods, from personal surveys to property prices and attributes, and beyond. For coastal protection services, production function methods, especially the EDF approach, are especially informative and yield estimates of value for decision makers. Replacement cost methods have been most widely used, largely because of the availability of data, but are most applicable for small-scale project level estimates of value of coastal protective services, and only then, if the conditions for their use are met. As Barbier's study demonstrates, replacement cost estimates can be far greater than the EDF approach. Further investigation is needed to determine whether hedonic approaches based on property prices can be used. Some of the key data for using any of these approaches to estimate coastal protection services include property value, past damages, and a measure of the expected damages.

Overall, the level of empirical knowledge on the value of protective services of mangroves and coral reefs is thin, especially relative to the understanding of the biophysical features of protective services. While the current coastal engineering models are sophisticated, the state of literature on the ecological valuation of protective services needs more rigor and applications in different settings. More work remains to be done in this area before standardized protocols are available for valuation. Fortunately the tools and knowledge from the engineering and insurance sectors can be rapidly adapted to help.

5.4| Ecosystem Services and Natural Capital Accounting

The System of National Accounts (SNA) is the most widely used set of information to monitor economic performance through such indicators as GDP and to carry out economic analysis for policy and planning. It has long been criticized for its incomplete accounting for natural resources and environmental services (Mäler 1991). The SNA does not account for the depletion of natural resources (minerals, oil, forests, and fisheries) in the production accounts and many ecosystem services more broadly. These resources are implicitly valued at zero when they are not included in national accounts (Dasgupta 2009). In response, the international community embarked on a process to develop a framework to expand the SNA for environmental accounts to fill this gap. A two-decade effort of conceptual and applied work to test out different approaches culminated in the System of Environmental Economic Accounting 2012-Central Framework (SEEA-CF), which the UN Statistical Commission adopted in 2012 as an international standard, similar to the SNA. The SEEA-CF is a satellite account to the SNA, meaning that it is closely aligned to the SNA through the use of common concepts, definitions, measurements, and classifications, but not fully integrated into the SNA accounts so that it does not change the fundamental SNA indicators and aggregates. The SEEA-CF includes asset and flow accounts, physical and monetary, for natural resources, energy, pollutants, land, environmentally related monetary transactions (taxes and subsidies), and macroeconomic aggregates and indicators.

The SEEA-CF is designed in a modular manner so that countries can implement the components that are most relevant to them, for example, water supply, and use tables or mineral asset accounts, but do not have to implement that entire set of accounts. The SEEA-CF has now been adopted for regular production by more than 30 countries, and other countries produce accounts on an occasional basis. While international agreement has been reached on SEEA methodology to account for individual natural resources, energy, and emissions, which together with the SNA cover most of the provisioning services and recreation, there has been growing interest in more comprehensive accounting for ecosystems, including the regulating services that are not covered in the SEEA-CF. A process was launched in 2006 to tackle the much more complex topic of ecosystem accounting. In 2014, the UN Statistical Commission accepted the SEEA-Experimental Ecosystem Accounting (SEEA-EEA, UN et al. 2014) as a best practice manual.

The SEEA-EEA provides general information on what has been considered so far and is a basis for further experimentation by practitioners in the long process to develop a statistical standard. There are a number of countries and agencies currently implementing ecosystem accounting. Canada is producing accounts for several ecosystems. Australia has produced accounts for the Great Barrier Reef (ABS 2015). The Netherlands is planning national coverage based on a pilot study of Limburg province (Edens et al. 2015). The United Kingdom has produced forest ecosystem accounts (Khan et al. 2013). Under the World Bank's WAVES program, the Philippines has constructed ecosystem accounts for two pilot sites, the Laguna Bay Basin (World Bank 2015a) and southern Palawan (World Bank 2015b) and several other countries are beginning work (Colombia, Guatemala, and Rwanda). The UN Statistics Division has launched a series of training workshops on the EEA for several countries, including Chile, Mexico, South Africa, and Vietnam. Academic studies have been carried out: for example, in Norway (Schroter et al. 2014); Indonesia (Sumarga and Hein 2014); and Peru (Conservation International 2015). Others have experimented with incorporating ecosystem services in national accounts, notably Barbier (2015) for Thailand, but this section focuses on the work that follows the SEEA-EEA framework.

Several points from country experiences are worth noting. First, most case studies implemented only physical ecosystem accounts with valuation limited to one or two services, and no attempt to value the entire asset. Ecosystem accounting has often focused on a few ecosystem services of greatest importance, rather than trying to cover all ecosystem services. There is a great advantage to constructing ecosystem accounts where there are comprehensive national statistics on land ownership that can be spatially aligned with an ecosystem, for example, catchment regions in Australia, Canada, the Netherlands, and United Kingdom. Among the WAVES pilot developing countries, only Rwanda has similar information, where every parcel of land is georeferenced in a national database.

5.5| The SEEA-Experimental Ecosystem Accounting

Components of EEA Accounts

The SEEA-EEA is designed to measure and value ecosystem assets and the services they provide. There is a focus on the challenge of the nonmarket ecosystem services that are invisible or "missing" from the SNA, since most of the market services—largely the provisioning and recreational services—are already captured in the SNA and do not need special treatment. It follows the same structure as the SEEA-CF and SNA, in that it encompasses biophysical accounting for physical flows and assets, and monetary accounts for both the flows and assets (for more detailed discussion of ecosystem accounts described in this section see UN et al. 2014).

Biophysical accounting in the SEEA-EEA

Physical asset accounts measure the biophysical stocks, such as the area extent of mangroves or coral reefs, producing ecosystem services at a specified point in time (UN ET AL. 2014). Ecosystem assets in the EEA are an ecosystem on the landscape: an explicit, spatially determined area containing biotic and abiotic components that function as a unit. In the EEA, ecosystem assets are measured by their extent and condition, and the expected flows of the full basket of "final" ecosystem services in the future.

The ecosystem asset could be the extent of a mangrove forest in a jurisdiction, as noted above. In terms of the basket of services, mangroves provide nursery habitat for important fish and crustaceans, carbon storage, flood protection, and wood products.

Spatial Units of Flows and Assets[30]

The first building block of an ecosystem account is land and one of the key considerations in measuring the biophysical accounts is the spatial unit of analysis. EEA is spatially explicit and uses three types of spatial units for ecosystem flow and asset accounts: Basic Spatial Units (BSU), Land Cover/Ecosystem Functional Units (LCEU), and Ecosystem Accounting Units (EAU).

BSUs are small spatial areas, typically a one-kilometer-squared grid, with relevant but basic information about the land they contain. These are aggregated into LCEUs. LCEUs are relatively homogeneous ecosystems whose processes are more closely linked internally than externally. For example, the nutrient cycles and energy flow around a coral reef more often flow back into the reef ecosystem than out into the shore or the open ocean. While the EEA suggests the use of the FAO Land Cover Classification System,[31] adopter countries are free to create their own organizing principles for LCEUs. For example, Australia uses their native National Vegetation Information System.[32]

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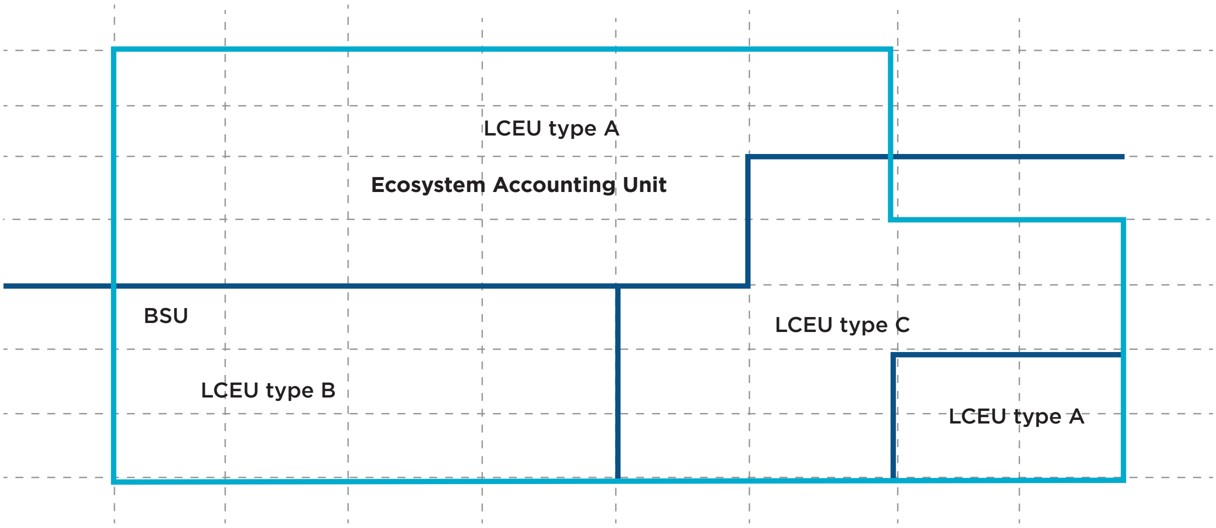
30 On the basis of a workshop on the SEEA-EEA held in April 2015, hosted by the UN Statistics Division, some of the terminology will be revised in a forthcoming technical note.

31 The FAO Land Cover Classification System based on universally applicable diagnostic criteria, such as whether an area is primarily vegetated, aquatic, and so forth, can be used to create a dichotomous, hierarchical classification system rather than a pre-defined set of classes. An example class that could emerge from the system is "multi-layered broadleaved deciduous forest." For more information see http://www.fao.org/docrep/003/x0596e/x0596e01e.htm.

32 The Australian experimental ecosystem account for the state of Victoria is compiled at the LCEU level, using the Major Vegetation Groups classification of the Australian National Vegetation Information System (FVIS; DSE 2013). Measurements of extent used in the asset account also came from existing extent statistics created by the FVIS, while condition measurements (DSE 2013) came from the ABS Experimental Land Accounts. The accounts are then aggregated up to the EAU level by grouping spatially within Catchment Management

Figure 5.3: Illustration of the Relationship between BSU, LCEU, and EAU



Source: Reproduced from Figure 2.4, UNSD (2013).

LCEUs can be further aggregated up into EAUs (see Figure 5.3). Creating EAUs takes into account administrative boundaries, natural features, and other characteristics, which create a cohesive unit of management interest, such as a river basin or a coral reef. Measurement can be made directly at each level, or BSUs may be aggregated into LCEUs and those into EAUs (and they may be similarly disaggregated in the same order). When referring to ecosystem services, guidance documents propose starting the recording and measurement at the scale of an LCEU for two reasons. First, BSUs that are at a fine scale have significant data requirements. Second, LCEUs are the smallest unit that can be used to represent holistic ecosystems, which is the scale that asset accounts are created.

In the case of mangroves and reefs, LCEUs and BSUs may be defined based on existing data and classifications. The LCEU for mangroves likely does not require further subdividing by mangrove type (or at least at present there is not a consistent habitat subclassification approach). Coral reefs can be subdivided into at least four reef types (barrier, fringing, patch, or shelf) based on existing reef classifications and the spatial data (for example, *http://data.unep-wcmc.org/datasets/1*).

To the extent that a further EAU is needed, this should likely parallel other national accounting units, such as census tracts, management areas, or provinces. Given the spatial resolutions of existing mangrove, reef and wave data, one square kilometer units are an acceptable BSU for these habitats. Reguero et al. (in review) propose another method for delineating coastal ecosystems by using one-kilometer-wide bands that run perpendicular to the shore, which has the benefit of tying the habitats (LCEUs) to the shoreline, where they can be more easily summed in to typical terrestrial administrative units (that is, EAUs). Regardless of the method or unit used, practitioners should take care in aggregating BSUs to ensure differing sizes do not create difficulties in comparing final values.

Authority (CMA), which cover the ten catchments within the state (DSE 2013). The CMAs provide the link between the EAU and socioeconomic data for valuation, since the Australian Bureau of Statistics reports land valuation data to the catchment level, allowing the EAUs to be directly overlaid with these data (DSE 2013).

In one approach to develop a monetary account of the biophysical flows and stocks (see discussion below), correspondence to economic units can be made when spatial units are delineated, such as through spatial overlay with land ownership or land use in each physical accounting unit. The correspondence is likely most precise at the BSU level. Using coarser scales (more aggregate spatial scales) may require additional assumptions. In one proposed approach, ecosystem services, whose benefits accrue to the public rather than to an individual institution, are recorded in the accounts to the "ecosystem" actor. Therefore, for these services, the economic correspondence is made when the LCEU is delineated.

Monetary accounting and aggregation of multiple ecosystem services

Because the SNA is based upon the concept of exchange value,[33] it is theoretically possible, when exchange values of ecosystem services have been estimated, to aggregate the values of all services provided by an ecosystems, much like aggregating the value of multiple products produced by a single factory. For example, to get the total value of ecosystem services in an EAU, sum each LCEU within the EAU and aggregate all the LCEUs to create a value for the entire accounting area. Another possible method would be to aggregate values by LCEU for the accounting area across all habitat types. For example, one could sum the value from all mangroves, coral reefs, forests, urban areas, and so forth in the EAU.

While the use of exchange values across the different habitat types hypothetically allows for the development of a single value, there are issues associated with combining use of other values or mixed values, where the basis for valuation may differ. Although it is simple in concept, this approach assumes that all services are likely to be independent and that the value added of interrelated services is netted out, that is, the total contribution of each individual service is counted exactly once (UN et al. 2014). Double counting is probable if dependencies between services are not considered. Resolution of the issue will require careful and thorough modeling of ecosystems.

Ecosystem asset valuation

In the absence of markets for assets, it is common to estimate the value of any asset as the present value of the stream of benefits the asset is expected to produce over its lifetime. This approach, for example, is described for valuing subsoil assets in the SNA and the SEEA. In principle, the ecosystem asset account can, be valued using the net present value (NPV) of all the expected future ecosystem service flows (whole basket of services) from the asset.[34] This concept is relatively straightforward for land, where there is a well-developed property market and for some natural resource assets, such as minerals and energy, for which an expected extraction path and prices are estimated.[35] It is less simple for ecosystems that provide a wide range of nonmarket, as well as market services. For example, for a single mangrove delineated as an LCEU that is expected to provide shrimp, fuel wood, flood protection, and recreation services for 50 years, the asset value of the LCEU is the present value of the aggregated exchange value of all of these services for 50 years. Over time, annual changes in the value of the asset account, based on new annual assessments of the flow of services, would then indicate whether the value of natural capital is increasing or decreasing over time. But this is an area where there are

[33] This concept will be further elaborated for the valuation of regulating ecosystem services in a forthcoming paper by the World Bank (2016).

[34] See Fenichel and Abbott 2014; and Fenichel et al. 2015 for an alternative approach.

[35] These projections are not simple but there is extensive experience with such projections for national balance sheets and the dynamics are not as complex as for ecosystems.

currently no clear guidelines and a great deal of discussion. The World Bank WAVES Program is further developing this work (World Bank forthcoming 2016).

The valuation of an ecosystem asset as the sum of the future stream of benefits requires a number of assumptions about the flow of future services and their value, which can be quite challenging. Many factors may affect the flow of services (from management of an ecosystem to exogenous factors, such as climate change) and their value. The London Group[36] is also considering another approach based on estimating ecosystem capacity to produce services.

The development of ecological production functions (see previous section) provides a modeling framework to make such long-run predictions and to understand the key characteristics of the complex socioecological system that are likely to have the greatest impact on the system through time. This exercise, whether with formal (bioeconomic) or informal (rules of thumb) modeling approaches, requires assumptions of business-as-usual human use of the ecosystem or continued sustainability of the ecosystem over time (UN et al. 2014). Some of these assumptions are likely to be violated. The advantage of formal modeling, therefore, is the ability to consider an ecosystem from many possible scenarios of economic use or ecosystem quality, which can be an intensive task.

Because of the tremendous challenges, there are not yet any examples of comprehensive asset valuation for ecosystems. However, a simpler approach to ecosystem asset valuation would be to value the asset on the basis of a single critical service, depending on the policy needs. In the case of coastal protection, for example, a policymaker might want to understand the trade-offs among hard infrastructure, natural infrastructure (such as mangroves), or a hybrid combination of hard and natural infrastructure. Typically assessments are based on the NPV over the expected lifetime of the asset, produced or natural. By valuing only the coastal protection service of mangroves and coral reefs, the asset value represents a lower bound on the asset value because of the omission of other services, such as fisheries habitat. Some of the considerations listed above must still be taken into account, but the calculation will be simpler than if one attempts to measure and value all ecosystem services. The advantage is that this approach is more readily implementable and can produce useful results for a policy maker.

5.6| Discussion

In general, while important progress has been made to develop and implement the SEEA-EEA, considerable challenges remain. The incremental approach where countries can choose the level of ambition best suited for them helps advance environmental accounting, despite the challenges. Australia's experiences in the state of Victoria and for the Great Barrier Reef region provide some lessons about what attributes ease implementation of an account. Australia had a great advantage in that national statistics on land ownership are spatially aligned with catchment regions, making those catchments excellent areas to choose as EAUs and greatly facilitating attribution of monetary information, if desired.

Countries beginning accounts could consider choosing EAUs that match existing spatially delineated economic or biophysical data to ease implementation. Australia and the United Kingdom used data that were already collected internally to measure extent and condition. Many developed countries are likely to have such data, and compilation of an asset account based on

[36] The London Group is an expert group established in 1994 by the UN Statistics Commission to develop methodology for SEEA. Technical papers can be found on the website maintained by the Un Statistics Division for the SEEA.

extent and condition may be a feasible first step and provide a spatial framework for the other accounts. Australia's decision to do only an example physical flow account, using existing data, is likely to provide similar valuable learning for countries that have such data available. But for developing countries, even this first step is likely to remain challenging. However, the increasing availability of remote sensing data is likely to make at least simple ecosystem accounting feasible in many countries in the near future. An important area of future research will be to determine to what extent ecosystem services can be estimated using remote sensing data.

The following bullets summarize key points for each subsection:

Valuing coastal protection services in the ecosystem accounting context

- There exists a large suite of tested tools for ecosystem service valuation. Each method is suited for some ecosystem services and each requires different types of data and data collection methods, from personal surveys to property prices and attributes and beyond.
- Several valuation approaches are both useful for costal protection services and are aligned with the concept of exchange value used in the SNA and SEEA.
- The Expected Damage Function approach is generally appropriate under the broadest circumstances and provides useful values for decision makers. The key factors include property value, past damages, and frequency of storm events. The development and greater use of biophysical models to assess the role of mangroves and coral reefs in preventing flooding and erosion could provide a systematic and consistent method to assess services. Some proxies for estimating property values for areas without well-established property registers are described in Chapter 4 and are likely to be relevant for developing countries.
- Replacement cost valuation methods based on engineering solutions, such as seawalls or breakwaters, are the most commonly used method to value coastal protective services, particularly flood protection and storm surge protection, but they only provide valid estimates of value under highly restrictive conditions. While project-level analysis is likely to fulfill most of the requirements for using replacement cost methods accurately, the appropriateness of this method needs to be assessed on a case-by-case basis. It is unlikely to provide accurate estimates at a larger scale (regional or national).
- Hedonic pricing methods may also provide useful information where there are well-functioning property markets. The approach relies on extensive data about property transactions and characteristics and may be challenging to implement in developing countries where extensive data on market transactions are often lacking.
- Overall, the level of knowledge on the economic value of ecological protective services of mangroves and coral reefs is thin, especially in comparison to the understanding of the biophysical features of protective services. It is difficult to make conclusions about the absolute magnitude and spatial variability of the value of protective services given these limitations, which can particularly limit the use of benefit transfer approaches.
- The methods for valuing the flow of coastal protection services are well defined and implementable, but serious challenges remain for measuring the asset value of the ecosystem providing this service.

Broader issues for ecosystem accounting

- Experience so far has indicated that it will not be simple to create an EEA account covering the full suite of ecosystem services for an entire country.

- It is best to start with a few key services, such as coastal protection services, recognizing that this underestimates the total asset value, but may be good enough for decision making.
- One should choose EAUs that match existing, spatially delineated economic or biophysical data to ease implementation. Many developed countries are likely to have such data. An increasing number of developing countries have good biophysical data, and remote sensing may provide useful information, but the economic data are typically not spatially aligned, making it difficult to go beyond physical accounts.
- It would be useful to implement pilot studies using information from historical events where data about storm intensity, flooding, economic damage, and so on are available to test and validate the approach described in this guidance note.
- Because the EEA is experimental, it will be important to develop a database describing how each country goes about developing the accounts in the future with special attention given to coastal protective services (and intermediate services more generally).

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Appendix 5.1: Nonmarket Valuation Techniques and Applications (adapted from Holland et al. 2010)

Type	Method	Description	Applicable Values	Example Application
Revealed Preference	Travel Cost	Examines recreational behavior in site choice, number of visits, and cost of visits to estimate recreational use values (Freeman 2003)	Recreation values; aesthetics	Hesseln et al. (2003) estimated recreation demand pre- and post-forest fire for national forest sites in Montana and Colorado.
	Hedonic (Property)	Analyzes determinants of property values to estimate site-specific use values (Freeman 2003)	Air quality, drinking water quality, surface water quality, noise, flood protection	Landry, Keeler, and Kreisel (2003) measured the value of an additional foot of beach width for beachfront homes.
	Averting Behavior	Examines costs incurred in alleviating the effects of reduced environmental quality (Freeman 2003)	Drinking water quality, air quality	Zivin et al. (2011) measured willingness-to-pay to avoid drinking water quality violations by expenditures in bottled water.
	Cost-based methods	Replacement cost uses costs of an engineering replacement to a lost environmental service (Boyer 2004); avoided cost uses costs that would be incurred if the service were lost	Flood mitigation, storm surge reduction, water filtration	Barbier (2007) estimated the value of flood protection from mangroves with the cost to replace them with breakwaters.

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Appendix 5.1: Nonmarket Valuation Techniques and Applications (adapted from Holland et al. 2010) *(continued)*

Type	Method	Description	Applicable Values	Example Application
	Simulated Exchange	Uses estimated demand and supply schedules to model hypothetical market exchange values (Oviedo et al. 2002)	Any use value	Oviedo et al. (2010) simulate the recreation value of a forest in southwestern Spain.
Stated Preference	Contingent Valuation	Uses survey methods to directly elicit individuals' estimates of their own willingness-to-pay (Freeman 2003)	Any; only this method type can estimate nonuse values	Loomis (2005) used contingent valuation surveys to measure the value of sea otters' nonmarket value to California households.
	Contingent Choice/Choice experiments	Uses individuals' responses to preferences between bundles of goods or scenarios to estimate willingness-to-pay (Freeman 2003)	Any; only this method type can estimate nonuse values	McGonagle et al. (2004) used a contingent choice experiment to measure the value of coastal open space access.
Economic-Ecological Method	Production Function (bioeconomic)	Estimates the value of an ecosystem good or service used to produce a final, marketed good (Freeman 2003)	Water provision, water quality, air quality, soil fertility	Barbier (2013) estimated the nursery value of a mangrove ecosystem for a fishery in Thailand.

Appendix 5.2: Summary of Studies Estimating Values for Coastal Protective Services and the Endpoints Measured

Authors	Year	Study Location	Coastal Services Valued	Endpoint Valued	Data Used	Conversion	Method of Estimating Value	Method of Estimating Physical Damages
Cesar	1996	Indonesia	Erosion reduction	NPV of land lost to erosion per km of coastline; total value of construction within 1 km of coast Dollar amount/km per year of property value (land, structures)			Avoided cost	Rule of thumb (1 km of coral reef damage leads to 1 km of shoreline damage; not used for valuation)
Bann	1997	Cambodia (Koh Kong Province)	Storm protection	Cost of housing construction in single village in a single year	Survey of village members	Amount of money of total existing housing construction costs for single year	Avoided cost	None
Berg, Ohman, Troeng, Linden	1998	Sri Lanka	Erosion reduction	Value of eroded land in dollar amount/km^2 reef/year			Property value	Sri Lanka Coast Conservation Department
Naylor, Drew	1998	Micronesia (Kosrae)	Coastal protection	WTP for coastal protection of the reef (unknown units)	Survey data	Respondents rank importance of storm protection and answer series of WTP questions	Contingent valuation	None
Ruitenbeek, Cartier	1999	Jamaica (Montego Bay)	Erosion reduction	Value of land along 34 km within 100 ft of the shoreline	Unknown	Dollar amount (NPV) of total land at risk of erosion	Avoided cost	None

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Appendix 5.2: Summary of Studies Estimating Values for Coastal Protective Services and the Endpoints Measured *(continued)*

Authors	Year	Study Location	Coastal Services Valued	Endpoint Valued	Data Used	Conversion	Method of Estimating Value	Method of Estimating Physical Damages
Sathirathai, Barbier	2001	Thailand	Erosion reduction	All damages to 75 m of coastline, in dollar amount/m^2 of mangrove	Cost/meter of constructing breakwater	Converted to dollar amount/m^2 of 75-meter-wide mangrove, discounted at 10 percent for 20 years	Replacement cost	None
Spurgeon	2002	Egypt	Erosion reduction	All damages to 7 km of coastline, in dollar amount/ha/year	Dollar amount/m of simple protection structure	Converted to value of 7 km length and 52.5 ha mangroves discounted at 10 percent in perpetuity	Replacement cost	None
Hargreaves-Al-len	2004	Sulawesi (Sampela)	Storm protection	Repair and total value of houses within "two rows" of shore	Unknown	Dollar amount of houses and repair costs	Avoided cost[3]	None
Emerton	2005	Meta	Coastal protection	Cost of housing construction in single village	Survey of village members	Dollar amount of total existing housing construction costs, for single year	Avoided cost	None
Gunawardena, Rowan	2005	Sri Lanka	Coastal protection[5]	All damages to 3 km of coastline, in dollar amount/m/year	Dollar amount/km per year of constructing protection structures for 10 years (not discounted)	Converted to value of 3km length of mangroves	Replacement cost	None

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Appendix 5.2: Summary of Studies Estimating Values for Coastal Protective Services and the Endpoints Measured *(continued)*

Authors	Year	Study Location	Coastal Services Valued	Endpoint Valued	Data Used	Conversion	Method of Estimating Value	Method of Estimating Physical Damages
Emerton	2005	Meta	Coastal protection	Cost of housing construction in single village	Survey of village members	Dollar amount of total existing housing construction costs, for single year	Avoided cost	None
Badola, Hussain	2005	India	Storm protection	Ordinal ranking of damage to homes from respondents in 3 villages; no numerical values reported	Survey data	Verbal reports of damages from large storm event divided into ranked categories; variances of responses compared (ANOVA method) across villages	Special[4]	Survey data
Barbier	2007	Thailand	Coastal protection	All damages to coastline, valued in dollar amount/m^2 of mangrove	Cost/meter of constructing breakwater	Converted to dollar amount/m^2 of 75-meter-wide mangrove, discounted at 10 percent for 20 years	Replacement cost	None
Barbier	2007		Storm protection	Marginal effect of loss of 1km^2 of mangrove area on economic damages from storms	Number of economically damaging storm events, from EM-DAT disaster database	Count data and regression models of number of economically damaging storm events and mangrove area	Expected damages	Unknown (EM-DAT disaster database method)

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Appendix 5.2: Summary of Studies Estimating Values for Coastal Protective Services and the Endpoints Measured *(continued)*

Authors	Year	Study Location	Coastal Services Valued	Endpoint Valued	Data Used	Conversion	Method of Estimating Value	Method of Estimating Physical Damages
Samonte-Tan, White, Tercero, Diviva, Tabara, Caballes	2007	Philippines	Coastal protection	All damages for unknown spatial area, reported in $ per year	Cost of constructing seawalls and dikes ($/year); unknown spatial area, size of structures, or how yearly value was computed		Replacement Cost	None
van Beukering	2007	Guam	Flood protection	5 percent of value of houses on entire island in zones susceptible to flooding in absence of coral reefs (determined through GIS analysis), in $/km^2/year	Average home value in flood-susceptible zones (unknown source)	5 percent total value in susceptible and non-susceptible areas compared; difference equated to storm protection value	Avoided cost	Rule of thumb
Burke, Greenhalgh, Prager, Cooper	2008	St. Lucia, Tobago	Coastal protection	Value of property in areas vulnerable to 25-year storm events (<5 m in elevation), in $/year	Internet search of home values in $/ft^2; range of values reported	Dollar amount per year for 25 years (not discounted) of property value of all vulnerable areas on both islands Weighted by "relative reef contribution" to shoreline protection	Avoided cost	None

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Appendix 5.2: Summary of Studies Estimating Values for Coastal Protective Services and the Endpoints Measured *(continued)*

Authors	Year	Study Location	Coastal Services Valued	Endpoint Valued	Data Used	Conversion	Method of Estimating Value	Method of Estimating Physical Damages
Cooper, Burke, Bood	2009	Belize	Coastal protection	Value of property in areas vulnerable to 25-year storm events (<5 m in elevation), in dollar amount/ft^2/year	Internet search of home values in dollar amount/ft^2; range of values reported	Dollar amount per year for 25 years (not discounted) of property value of all vulnerable areas on both islands Weighted by "relative reef contribution" to shoreline protection	Avoided cost	None
Das, Vincent	2009	India (Orissa)	Human mortality	Number of deaths following storm events; no conversion to valuation	Administrative data	Regression of mangrove width (obtained from GIS data) to deaths from catastrophic storm	Expected damages approach	Empirical estimation
Cruz-Trinidad, Geronimo, Cabral, Aliño	2011	Philippines	Storm protection	All damages to 37 km of coastline, reported in $/km^2			Replacement cost[1]	None
O'Garra	2012	Fiji	Coastal protection	All damages to 8 km of coastline, in dollar amount/km/year			Replacement cost[2]	None

[1] Values were transferred from David et al. 2010. Climate Change in Coastal Areas: A Community-based Adaptation Approach. Final Report
[2] Used benefits transfer for values.
[3] Values transferred from Cesar 1996.
[4] This study did not provide an economic value of the ecosystem service. Instead, the authors determined that there were statistically significant differences in damages following a storm event for villages with varying levels of mangrove protection.
[5] Here "coastal protection" means that the study authors either specified general coastal protection as the service being valued, or mentioned multiple services (such as erosion reduction or storm damage reduction) for which they estimated a single value.

6| Coastal Protection Services from Coral Reefs and Mangroves in Policy and Practice: Case Studies

Michael W. Beck,[h,i] Montserrat Acosta-Morel,[h] Siddharth Narayan,[j] and Pam Rittelmeyer[i]

6.1| Summary

There is now a large and growing body of scientific evidence on reef and mangrove coastal protection services. This chapter explores how that evidence has been used to make better-informed decisions and to understand the incentives for these decisions. It presents relevant case studies where the coastal protection benefits of mangrove and coral reef habitats were explicitly linked to coastal zone management and habitat restoration decisions. These studies offer compelling lessons on how coastal protection benefits have influenced coastal management decisions.

The coastal protection benefits of mangroves and reefs have been deeply influential in both policy and practice. More than 20 case studies were found and these could be grouped into five major categories to identify the range of decisions influenced by the coastal protection role of reefs and mangroves: (i) planning and land use decisions, including coastal zone management; (ii) coastal defense infrastructure projects; (iii) national risk and adaptation planning; (iv) habitat restoration; and (v) post disaster recovery. There are clear examples over the last several decades where these perceived and measured benefits have led to significant habitat conservation and restoration actions and changes in coastal policies. From review of the policies and projects, lessons learned and opportunities to advance the use of mangroves and coral reefs for coastal protection were identified. Most importantly, there have been a number of key triggers behind policy change and decisions supporting natural coastal protection, including the following: (i) community-based demand for coastal protection, particularly from mangroves; (ii) clear scientific evidence in ecology, economics, and engineering of protection benefits and cost effectiveness of nature-based defenses; (iii) international obligations and funding, particularly for green climate adaptation; (iv) post-disaster rebuilding and restoration that incorporates ecosystems; and (v) demand for other benefits, such as food security and jobs with natural coastal protection as an ancillary benefit.

6.2| Introduction

The world's coastal zones are changing rapidly because of coastal development and climate change; both of which will dramatically increase the risk of catastrophic damage to coastal communities. Erosion, inundation, and extreme weather events affect hundreds of millions of vulnerable people, important infrastructure, and tourism with significant losses to national economies and major impacts on livelihoods. There have already been huge losses of coastal habitats to development, which raises future risks by further exposing communities and assets to more intense waves and winds.

Coastal and marine habitats, particularly coral reefs and mangroves, can substantially reduce vulnerability and risk, providing "natural protection" from waves and storms. Yet the value of these systems for natural and nature-based defense is still not fully recognized. Meanwhile, these systems continue to be lost and degraded. In terms of loss statistics, there has been 30 to 50 percent habitat loss for wetlands (Zedler and Kercher 2005), 19 percent loss of mangroves from 1980–2005

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[h] The Nature Conservancy.
[i] University of California Santa Cruz.
[j] University of California Santa Barbara.

(Spalding et al. 2010), and 75 percent of the world's coral reefs are now rated as threatened (Burke et al. 2011). Often, the loss of these habitats is greatest around population centers. That is, exactly where the most people could benefit from these ecosystems is often where their impacts and loss have been the greatest. Without changes in both policy and perception as to the value of these systems, societies can expect the trends in habitat loss to continue.

While mangroves and reefs face growing threats, there is opportunity to guide policy actions toward conservation and restoration. Governments and businesses are showing increasing interest in identifying where natural habitats and nature-based defenses can be cost effective for coastal defense (for example, CCRIF 2010; van den Hoek 2012; NYC 2013; Temmerman et al. 2013).

This section identifies how information on reef and mangrove coastal protection services has been used to inform decision making from the national to local scales. Coastal protection services are increasingly accounted for in making decisions that go beyond SEEA and related approaches that are covered in Chapter 5. However, there is a long way to go before consideration of natural coastal protection alternatives becomes standard practice. This section identifies how and where natural coastal protection services have been used successfully in the past to influence decisions in the policy and practice of coastal management. This information is distilled in the section on lessons learned and needs and opportunities to inform the future development of policies and projects that use mangroves and reefs for coastal protection.

6.3| Methods

Case studies that linked coastal protection benefits to reef and mangrove conservation and restoration decisions were identified. Most often, the case studies were targeted at specific governmental decisions. Most of the studies included clearly led implementation actions (such as habitats restored). Some studies were included, if governmental bodies commissioned or led them (such as revisions to coastal zone management plans) and the studies were clearly aimed at informing specific policies and decisions, even if the implementation was only considered to be in progress.

This review only considered case studies on mangroves and reefs. It did not take into account examples from marsh and oyster reef habitats, although there are many examples of these systems providing similar protective services. It also did not look at studies that only measured ecosystem services (see Chapter 5), unless they were aimed at a very specific decision. Scientific studies that measured services from existing habitats were also not included. For example, the studies examined in the Ferrario et al. (2014) reef review paper were not considered, because these studies mainly measured services in situ. Many of these broader ecosystem services studies are surely influencing decisions, but the focus for this review was on examples where the link to decisions was explicit.

In addition, the review only considered projects that were designed to deliver some coastal protection services. For example, there are thousands of reef restoration projects around the world, but most are designed for fishery benefits, not coastal protection. Projects that were not designed to restore or enhance existing habitats were excluded. For example, the review did not include reef beach projects (see www.reefbeach.com) as most of these projects put artificial reef structures in sandy nearshore environments that did not previously have reef habitat.

6.4| Results: The Influence of Protective Services on Coastal Policies and Practices

The review identified more than 20 case studies where the coastal protection services of mangroves and reefs have been used in making decisions (Table 6.1). These examples are extensive, but not exhaustive. Table 6.1 highlights some of the key characteristics of all of these studies and the subsections below address eight of the case studies in greater depth.

The projects can be classified in to five main types:

a. *Coastal Zone or Land-Use Decision*s—Where accounting for ecosystem services and marginal values can influence land use, zoning, and development decisions.

b. *Coastal Defense Infrastructure Projects*—Where natural or nature-based defenses can be directly conserved and restored to contribute to risk reduction and coastal protection.

c. *National Risk and Adaptation Planning*—Where ecosystem conservation and restoration priorities are identified for their coastal defense and risk reduction benefits.

d. *Habitat Restoration*—Where ecological restoration programs consider ecosystem services, such as coastal protection in the selection and design of projects.

e. *Post Disaster Recovery and Restoration*—Where after a storm or tsunami there is support for the restoration of natural and nature-based defenses.

6.5| Case Studies

a. Coastal zone or land-use decisions

There are few examples where coastal protection services from reefs and mangroves are influencing coastal zoning or land-use decisions at a large scale, such as national level (Table 6.1). These examples are the rarest cases, which is not surprising given that they represent change at a significant geographic and political scale. The examples from the Philippines provide the clearest examples of long-term coastal planning with coastal protection specifically in mind.

Case Study 1: National Coastal Greenbelt Program of the Philippines: Coastal development in the Philippines has led to more than a 50 percent loss of mangroves since 1900, mainly because of conversion for aquaculture (Primavera 2005; Primavera et al. 2014). Between the 1950s and the 1970s, the government implemented a pro-aquaculture policy under the assumption that the mangroves were wastelands and of little value. In the 1970s, scientists began to document the importance of mangroves to coastal fisheries and the government began to mandate some mangrove protection. Over the past four decades, there have been a number of laws aimed at restoring a greenbelt of mangroves along the coastline of the Philippines. However, violation of the laws is common, and enforcement is lacking. Furthermore, the laws, policies, and regulations have been fragmented and, at times, conflicting.

The emergence of scientific proof of the benefits of mangroves as protection from waves and storm surges (as well as the direct experience from communities that are frequently exposed to impacts of major storms) has fueled development of a comprehensive National Coastal Greenbelt Action Plan. This plan, which is to be implemented at both the national and local levels, includes protection of mangroves for both conservation and risk reduction through the establishment of a 100-meter-wide protection zone of mangrove and beach forest vegetation between the sea and land, initially for the eastern Pacific seaboard of the Philippines, where typhoons make landfall. The plan is contained in Senate Bill 2179, the National Coastal Greenbelt Act of 2014, which is under consideration by the Senate of the Philippines as of May 2014 (see Appendix 6.1).

In sum in the Philippines, (i) there has been significant mangrove loss, (ii) laws and regulations have existed for decades to protect mangroves for their benefits to fisheries, but have lacked implementation, and (iii) recent storms coupled with stronger scientific information have increased support and action for mangroves.

Table 6.1: The Use of Protection Services from Mangroves and Reefs in Coastal Policies and Practices

Location	Decision Target(s)	Type of Information	Key Factors & Lessons Learned	References
a. Coastal Zone Management Planning & Land Use Decisions				
Philippines	Senate Bill 2179, the National Coastal Greenbelt Act of 2014	• Literature-based Values	• Act under consideration includes protection of mangroves for both conservation and risk reduction. • Senator Aquino's letter of introduction for the act includes literature-based values of role of mangrove in percent reductions in wind and swell waves and storm surge. • Legislation stalled; renewed interest after Typhoon Haiyan. • Act includes development of a National Coastal Greenbelt Action Plan and a Local Coastal Greenbelt Action Plan. • Act includes long-term program for community-based rehabilitation, as well as restoration implemented by the municipality and coordinated by the Department of Interior and Local Governments (DILG).	Senate of the Philippines (https://www.senate.gov.ph/lis/bill_res.aspx?congress=16&q=SBN-2179)
Belize	Belize Coastal Zone Management (CZM) Plan	• Scenario Analysis	• The CZMAI was tasked with developing a coastal zone management plan with the help of alternatives assessed with InVEST. • Scenario analysis helped identify likely trade-offs in benefits and competing interests. • Three ecosystem services considered: lobster fisheries, tourism, and coastal protection. There is a tradeoff among services (for example, development scenarios led to loss of coastal protection services but increases in tourism revenue). • It was difficult to get stakeholder input to identify alternative national scenarios • The analyses helped identify appropriate indicators for CZM.	Arkema et al. 2015
Seven States bordering the South China Sea & Gulf of Thailand: Vietnam, Cambodia, China, Indonesia, Malaysia, Philippines, Thailand	Strategic Action Programme (SAP) for the GEF Project, "Reversing Environmental Degradation Trends in the South China Sea and Gulf of Thailand"	• Cost-benefit Analysis (CBA)	• CBA values could be estimated by country. • CBA values varied across the geography. • CBA values could be calculated against the targets identified in SAP. • Mangrove conservation and restoration could be shown to be cost effective. Costs of implementing measures were less than the benefits received. • CBA was estimated to be highly conservative, because it did not use benefits transfer approach.	Pernetta et al. 2013

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Table 6.1: The Use of Protection Services from Mangroves and Reefs in Coastal Policies and Practices *(continued)*

Location	Decision Target(s)	Type of Information	Key Factors & Lessons Learned	References
b. Coastal Defense Infrastructure Projects				
Vietnam (8 Provinces)	Red Cross-led Mangrove Restoration Projects	• Inferred Values[a] (initially) • Cost-benefit Analyses (completed later)	• 8,961 hectares and about 100 kilometers of dyke lines restored. • Damages to dykes have been reduced by about $80,000–$295,000 in studied communities. • Mangrove restoration led to an increase in aquaculture yields providing income for communities. • Mangrove reforestation was highly cost-effective. • The benefit-cost ratio (BCR) was always greater than 1. Ranged from three to 68 without considering ecological benefits and from 28 to 104 with ecological benefits. • The biggest ecological benefit was blue carbon mitigation.	IFRC 2011
Bangladesh	Government-led Mangrove Restoration	• Inferred Values • Cost-benefit Analyses (completed later)	• 120,000 hectares of mangrove restored. • Observations about inferred protection benefits of mangroves in Sudarbans motivated initial mangrove restoration efforts (about 1,966 by Forest Department). • Mangrove restoration was very effective in land-building and there was rapid sediment accretion. • Land-building led to changes in plant communities (succession) to less intertidal species; successional changes need to be planned. • Mangrove monocultures developed more problems than multi-species mangrove plantations. • The protection has provided 60,000 hectares of stabilized land (about 800 per hectare).	Saenger and Siddiqui 1993
Guyana	Government-led Mangrove Restoration	• Inferred Values • Cost-benefit analyses (completed later)	• A US$5M project for mangrove restoration is being implemented. • Climate change funding (EU Global Climate Change Alliance Programme) is motivating restoration. • Mangrove restoration for coastal protection is encouraged through earmarking of EU adaptation funds for sustainable coastal zone management. • Despite past push on hard engineering structures, current government is also promoting mangrove regeneration (via Mangrove Action Committee). • The success/failure of mangrove restoration depends strongly on appropriate topography.	Anthony & Gratiot (2012)

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Table 6.1: The Use of Protection Services from Mangroves and Reefs in Coastal Policies and Practices *(continued)*

Location	Decision Target(s)	Type of Information	Key Factors & Lessons Learned	References
b. Coastal Defense Infrastructure Projects *(continued)*				
American Samoa	US Department of Commerce & Government of American Samoa	• Inferred values • Literature-based values	• American Samoa suffers major coastal erosion. • Resource economic valuation was used to further coastal habitat management by Coral Reef Advisory Group of the Governor. • Using the Replacement Cost method, the economic value of coral reef shoreline protection was estimated as US$0.06 per square meter (discounted at 3 percent over 100 years) for a national total of US$447,000 per year. • Mangroves only exist in a 0.5 square kilometer area in the country. The value of these mangroves was estimated at US$8.89 per square meter for a total value of US$135,000 per year.	Spurgeon et al (2004)
Commonwealth of the Northern Mariana Islands (CNMI)	Coastal Resources Management Office of the CNMI. Specifically intended as a follow-up to the previous CNMI Three Year Coral Reef Protection Local Action Strategy, LAS (2003).	• Inferred Values • Cost-benefit Analyses	• The Coastal Resources Management Office initiates estimation of storm protection of Saipan's coral reefs. • Level of protection estimated by mapping the reefs and using information from neighboring regions. • Using data on coastal assets behind reefs and the expected frequency of storms the economic value of coastal protection by the reefs is estimated at US$8.04 million per year. • Coastal protection is the second most valuable service offered by Saipan's reefs after tourism.	van Beukering et al. (2006)
Malaysia	Government-led mangrove restoration; Department of Irrigation and Drainage (DID)	• Literature-based Values	• Around 60 percent of existing earth bunds along peninsular Malaysia's coastline cannot survive erosion at current rates. • The mangrove ecosystems of Peninsula Malaysia are estimated to provide around US$0.22 million per kilometer. • The DID recommended protecting and restoring a 400-meter buffer zone of mangroves (a conservative estimate of the width required). This recommendation was based on mangrove numerical models and expert advice. • The DID is experimenting with a combination of artificial and natural protection. A pilot study of a 1.4 kilometer length of coast proved successful and was extended to another 1.2 kilometers.	Othman (1994), Chong (2006)

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Table 6.1: The Use of Protection Services from Mangroves and Reefs in Coastal Policies and Practices *(continued)*

Location	Decision Target(s)	Type of Information	Key Factors & Lessons Learned	References
b. Coastal Defense Infrastructure Projects *(continued)*				
Fiji	Lami Town Council	• Cost-benefit Analyses • Inferred Values • Scenario Analyses	• Lami Town Council assessed coastal risk reduction options for future extreme events. The options assessed, including hard engineering options (e.g., seawalls, dikes), natural options (e.g., mangrove and reef protection), and a combination of the two. • The unit costs of the natural options was up to 100 times less than the engineering options. Cost-benefit ratios were estimated as 19.5 for natural options, nine for engineering and eight to 15 for hybrid options. • The assessment recommended protecting and maintaining existing mangroves, reefs and other habitats as a priority action. • Nonetheless the assessment recommended targeting engineering options to protect priority areas of built capital given uncertainties in implementing natural options.	Rao et al. (2013)
c. National Risk and Adaptation Planning				
8 Caribbean Nations-Anguilla, Antigua & Barbuda, Cayman Island, Bermuda, Barbados, Jamaica, St. Lucia & Dominica	Caribbean Catastrophic Risk Insurance Facility, a multi-country risk pool and regional catastrophe fund	• Cost-benefit Analyses	• Joint industry/government facility • Used approaches developed by the Economics of Climate Adaptation Working Group. • Reef and mangrove restoration was more cost effective than breakwaters across all eight nations (though only benefit considered was coastal defense). • Moreover, reef and mangrove restoration was one of the most cost-effective of all approaches in seven of eight nations. • Analyses indicate cost-effective measures at national level, but are not scaled down further.	CCRIF 2010
Solomon Islands	National Adaptation Program of Action	• Inferred Values • Literature-based Values	• Mangroves and coral reefs ecosystems are recognized for their coastal protection service. • Coastal erosion and degradation are environmental problems affecting properties and land. • Program calls for actions to "Protect and where relevant rehabilitate coral reefs and mangroves in build-up coastal areas" (Objective1, Outcome 2).	Ministry of Environment, Conservation and Meteorology 2008

(continued on next page)

Table 6.1: The Use of Protection Services from Mangroves and Reefs in Coastal Policies and Practices *(continued)*

Location	Decision Target(s)	Type of Information	Key Factors & Lessons Learned	References
c. National Risk and Adaptation Planning *(continued)*				
Dominican Republic	National Adaptation Program of Action	• Inferred Values • Literature-based Values	• Coral reef ecosystems are recognized as natural defenses. • Degradation of coastal ecosystems has generated losses to the tourism and housing infrastructure. • Plan proposes reforestation of coastal area to reduce erosion, improve coastal defenses, and maintain biodiversity.	SEMARENA 2008
Maldives	National Adaptation Program of Action	• Inferred Values • Literature-based Values	• Program identifies need to "Protect coasts through soft infrastructure" (obj 6.1.1.5) and to "protect house reef to maintain natural defense of islands" (obj 6.1.1.6).	Ministry of Environment, Planning & Water 2007
CARICOM	Implementing the CARICOM Regional Framework for Achieving Development Resilient to Climate Change	• Inferred Values • Literature-based Values	• Approved by the heads of government of member states in 2012. • Rely on economic analyses of Bueno et al. 2008, "The Caribbean and Climate Change: Costs of Inaction" to strengthen case for a climate change strategy. • This is the underlying framework for CARICOM state adaptation initiatives, but the documents are very general and broad.	CCCCC 2012
d. Habitat Restoration				
Maldives	Marine Research Section, Public Works Department	• Inferred Values • Cost-benefit Analyses (completed later)	• Observations of reef degradation and increased shoreline erosion motivated restoration experiments. • Several pilot coral-reef restoration projects implemented and their cost-effectiveness was compared. The main goals were coastal protection and fish production. • At the time of the study, the project's coastal protection values were still being evaluated. Habitat restoration effectiveness was measured. Reef structures had higher fish populations within a year, but community structure was different than control reef flats.	Clark and Edward 1999

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Table 6.1: The Use of Protection Services from Mangroves and Reefs in Coastal Policies and Practices *(continued)*

Location	Decision Target(s)	Type of Information	Key Factors & Lessons Learned	References
d. Habitat Restoration *(continued)*				
India	Gujarat State Forest Department, Gujarat Ecology Commission, others	• Cost-benefit Analyses (based on a survey)	• An eco-development program was developed and implemented for villages along the Gulf of Kuchch region in Gujarat. • Project objectives included the following: contributing toward increased acceptance of the need to protect, conserve, and regenerate mangroves and reefs by local communities, institutions, and industries; to increase mangrove and reef cover; and to enrich marine and coastal biodiversity. • The model also included participation by private sector companies and compliance in allocating an area for green belt development. • The success in mangrove restoration in Gujarat is attributed to the adoption of a community-based restoration model. The CBMR program resulted in an increase in mangrove extent by 8,346 hectares. This included a shelter-belt of 1,500 hectares. • A 31.5 percent increase in income from fisheries was reported as a result of mangrove planting, among other advantages.	Viswanathan, 2013; WAPCOS Limited, 2009
e. Post-Disaster Recovery/Restoration				
Philippines	Mangrove Restoration	• Inferred Values • Literature-based Values	• There was an immediate $8 million investment in mangrove restoration post-Haiyan. • Widely held belief—even among villagers—that mangroves served coastal protection purposes during Typhon Haiyan in areas where they had not previously been converted for aquaculture. • Aims for restoration program were both social (a cash-for-work program and risk reduction) and ecological (habitat restoration). • There were conflicting opinions about how best to meet these joint goals with concerns that aims to plant quickly can lead to ecologically inappropriate approaches (for example, trampling recovering mangroves or planting mangroves in seagrass beds).	*http://www.mindanews.com/top-stories/2014/04/04/p1-b-budget-for-mangrove-planting-in-leyte-samar-too-much-says-expert/*

[a] Inferred Value—Quantitative coastal protection did not appear to be used to justify decisions, but perspectives by stakeholders were clearly cited as central to influencing decisions.

Case Study 2: Coastal Zone Management in Belize: The government of Belize tasked the Coastal Zone Management Authority and Institute (CZMAI) with the design of the Integrated Coastal Zone Management Plan. To inform its development, the CZMAI partnered with the World Wildlife Fund (WWF) and the Natural Capital Project (NatCap), who together focused in particular on three critical ecosystem services: lobster fisheries productivity, recreational activities, and coastal protection. NatCap developed an integrated database on biodiversity, habitats, and marine and coastal uses. Then, together with local stakeholders, the team formulated three possible future scenarios: a conservation scenario emphasizing sustainable use and investment in coastal habitats; a compromise ("informed management") scenario that advanced development and conservation; and an infrastructure development scenario. These scenarios were then examined in the InVEST tool (see Chapter 4 for more information on this tool) to examine the tradeoffs among options as they relate to the value of the services in each location, the quantity of services provided, and iterations of other possible scenarios.

The importance of coastal protection in the scenarios was clear. The benefits of coastal protection, measured in terms of damages avoided, totaled billions of Belizean dollars, whereas other benefits (tourism and lobster fisheries) totaled in the millions of BZ dollars (Figure 6.1). There was significant trade-off in benefits. For example, more development would generate a higher recreation value, but also much higher damages to infrastructure because of the loss of coastal habitat protection. In these efforts, the development of appropriate alternative scenarios proved to be one of the greatest difficulties in the assessment of benefits; it was difficult to get stakeholders to visualize and articulate future scenarios, particularly at a national level (A. Guerry pers. comm.; Gleason et al. 2010; Halpern et al. 2012).

The CZMAI finalized and submitted the Coastal Zone Management Plan in September, 2013, but as of April, 2014, the plan had yet to begin implementation pending formal restructuring and reestablishment of the Board of Directors of CZMAI and Cabinet endorsement. Nevertheless, this case study provides valuable insight into the development of future coastal zone management plans in the region. By categorizing marine and coastal uses and visualizing them in maps, interest groups were better informed in their conflict resolution and negotiation of competing interests.

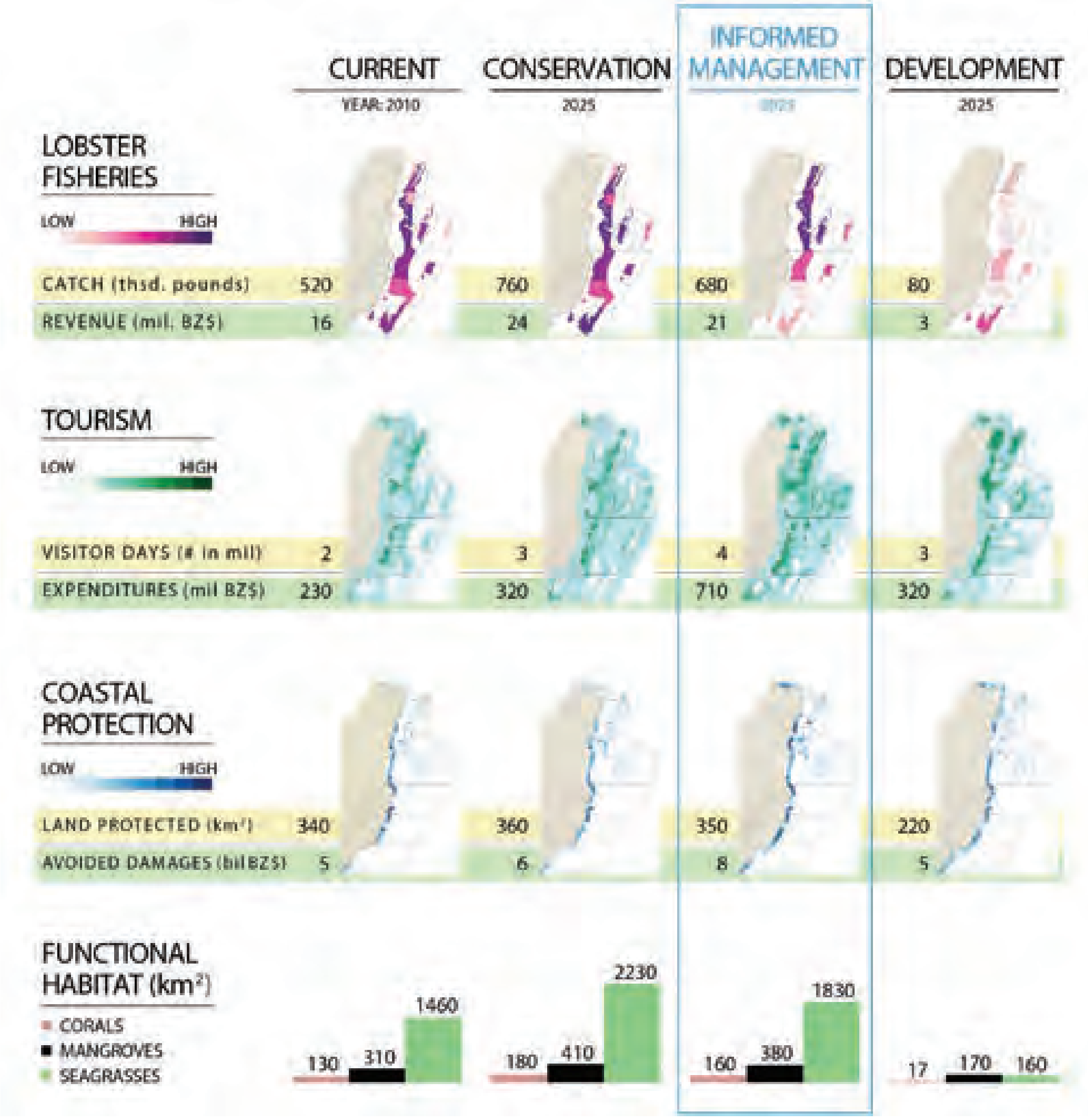
In sum, (i) the CZMAI was tasked with developing a coastal zone management plan with the help of alternatives assessed with InVEST and (ii) the scenarios developed in stakeholder workshops were useful in presenting land-use tradeoffs to decision makers.

b. Coastal defense infrastructure projects

There are a growing number of projects where mangrove and reef habitats were restored or enhanced for coastal protection (Table 6.1). These were the easiest studies to assess and draw linkages between protection benefits and management decisions. It is particularly noteworthy that some of the projects have grown to include thousands of hectares of restored habitat.

Case Study 3: Breaking the Waves: Impact Analysis of Coastal Afforestation for Disaster Risk Reduction in Vietnam. Mangroves form an integral part of the coastal ecosystem of Vietnam, although mangrove cover has been drastically reduced by deforestation and commercial activities in recent times. The Ministry for Agriculture and Rural Development (MARD) attempted mangrove reforestation as early as the 1960s without much success. In 1993, the MARD chapter in the commune of Thai Binh proposed a renewed mangrove reforestation effort for coastal protection to be headed by the Vietnam Red Cross (VNRC). This work was expanded to multiple communes over 17 years with a total of $8.88 million spent on restoration. Mangrove cover has

Figure 6.1: Current Distribution of Habitats and Services (2010) and the Distribution of Habitats and Services (rows) under Three Different Future Scenarios (columns) (From Arkema et al. 2015)



since increased by nearly 9,000 hectares and about 100 kilometers of sea dyke are now protected by VNRC-planted mangroves. These restoration efforts were often integrated with artificial defenses (dykes) from the beginning.

The mangrove reforestation efforts were assessed for their cost-effectiveness and were found to be highly beneficial across all eight communes. Benefit-cost ratios (BCRs) were positive, varying from 3:1 to 28:1 (Table 6.2), even when only a few services were valued. Mangrove reforestation proved effective in three communities that experienced storms, with much less flooding and sea dyke damage compared to similar storms that struck before the mangroves were planted. The

Table 6.2: Estimated Benefits and Costs in Selected Communes (adapted from IFRC 2011)

Commune	Dai Hop	Thai Do	Nam Tinh	Giao An	Dien Bich
District	Kien Thuy	Thai Thuy	Then Hai	Giao Thuy	Dien Chau
Province	Hai Phong	Thai Binh	Thai Binh	Nam Dinh	Nghe An
Timeframe of planting	1998–2005	1994–2005	1997–2005	1997–2005	1998–2005
Planted area (hectares)	450	900	380	678	100
Planting costs ($)	425,866	858,373	362,424	646,641	95,374
Protective benefits ($)	676,868	15,330,243	n.a.	37,818,545	n.a.
Direct economic benefits ($)	682,094	672,436	4,799,476	6,748,533	344,931
Ecological benefits ($)	10,989,000	32,730,828	12,307,055	23,308,814	3,437,879
Benefit/cost ratio (excluding ecological benefits)	3.06	18.64	13.24	68.92	3.61
Benefit/cost ratio (including ecological benefits)	28.86	56.77	47.20	104.96	39.66

avoided damages in these communities were estimated at $80,000 to $295,000, which are quite substantial values given that the GDP per person in Vietnam is less than $1,300.

The initial restoration efforts were motivated less by formal valuations and benefit: cost analyses (BCAs) than by experiences of aid group and village leaders. These stakeholders identified that mangroves provided benefits to lives and livelihoods. These efforts then served as the basis for quantitative BCAs, which may have also motivated later restoration efforts.

In sum, in Vietnam, (i) the MARD and VNRC initiated a mangrove reforestation project to enhance and protect existing sea dykes and provide coastal protection; (ii) the project was successfully extended to a total of eight communes covering 100 kilometers of sea dykes and nearly 9,000 hectare of mangrove cover by 2010; and (iii) the projects were highly cost effective.

Case Study 4: Economic Valuation of Coral Reefs and Adjacent Habitats in American Samoa: The coral reefs of American Samoa are some of the country's most valuable assets. The Department of Commerce (DOC) established the American Samoa Coastal Management Program (ASCMP) in 1980 to protect and preserve its natural coastal resources, while ensuring sustainable development. American Samoa suffers from an extreme coastal erosion problem. Under the ASCMP, the Governor's Coral Reef Advisory Group (CRAG) identified economic evaluation of coral reef resources as a necessary tool for advancing understanding and management of the reefs. In this regard, the DOC commissioned an economic evaluation of American Samoa's coral reefs and adjacent habitats.

The report identified that coral reefs were estimated to be worth $11 million per year in the region in 2004, of which use values were approximately $1.4 million per year (Table 6.3), with shoreline protection contributing roughly one third of the use values. Estimates of current erosion rates and future shoreline protection measures indicate a cost saving of around $447,000 per year

Table 6.3: Value of Coral Reefs in American Samoa (adapted from Spurgeon et al. 2004)

Ecosystem service	Valuation method	Total value (millions, $)
Subsistence and artisanal fishery—direct and indirect uses (producer surplus)	Net factor income	0.75
Subsistence fishing (consumer surplus)	Value transfer	0.08
Diving/snorkeling (producer surplus)	Net factor income	0.03
Diving/snorkeling (consumer surplus)	Value transfer	0.05
Shoreline protection	Replacement cost	0.49
Nonuse benefits	Contingent valuation	9.61
Total Economic Value		**11**

($2,000/ square kilometer/year) from the existing 64 square kilometers of coral reefs near eroding coastlines. These relatively low values for coastal protection benefits are a reflection of the low extent of coastal infrastructure in the country. The vast majority of the coastal protection value came from coral reefs along a single section of shoreline on the south shore of Tutuila with a concentration of settlements and shoreline infrastructure.

The report also estimated the economic value of the 0.48 square kilometers of mangrove forest that remains in American Samoa at a total of $1.5 million per year in 2004. Around 12 percent of this value was from direct use values of which coast and flood protection was the largest contributor, estimated at $135,000 per year. Similar to the reefs in Tutuila, all this value was concentrated in a single section of mangrove forest in the Pala region.

In sum, (i) the U.S. Department of Commerce valued American Samoa's coral reef and mangrove habitats to inform its coastal management program; (ii) shoreline protection was estimated at $447,000 per year for reefs and $135,000 per year for mangroves; and (iii) low values reflected the lack of property behind these habitats.

c. National risk and adaptation planning

There is increasing emphasis being placed on the development of National Risk Reduction Plans and National Adaptation Plans (NAPs). As these plans are new, it may be easier to include natural coastal protection benefits in them and reflect the latest rapid advances in the science and practice of ecosystem-based adaptation.

In 2011, during the United Nations Climate Change Conference in Durban, South Africa, governments agreed to develop NAPs to assess their vulnerabilities, mainstream climate change risks, and prioritize adaptation measures. The NAP initiative was supported by the National Adaptation Programs of Action (NAPA), which were developed by many of the least-developed and developing countries to communicate priority activities addressing urgent and immediate needs for climate change adaptation.

Case Study 5: Caribbean Catastrophic Risk Insurance Facility—Economics of Climate Adaptation: The Caribbean Catastrophic Risk Insurance Facility (CCRIF) is a risk-pooling facility owned, operated, and registered in the Caribbean for its governments. It is designed to limit the financial impact of catastrophic hurricanes and earthquakes to Caribbean governments by quickly providing short-term liquidity after extreme events. It recently examined costs and benefits of some 20 approaches for coastal risk reduction and adaptation (for example, from mangrove restoration to new building codes) in eight Caribbean nations using an approach developed by the Economics of Climate Adaptation Working Group (CCRIF 2010). It found that reef and mangrove restoration were more cost effective than breakwaters across all eight nations, even though the only ecosystem service considered was coastal defense. Moreover, reef and mangrove restoration was one of the most cost-effective of all approaches in seven of eight nations.

Using information provided by CCRIF and others (such as Bueno et al. 2008), the Caribbean Community (CARICOM) through the Caribbean Community Climate Change Centre (CCCCC) has developed several documents to frame their climate change adaptation actions. These actions include general coordination among states, funding resources, mitigation measures, adaptation efforts, and monitoring and enforcement in each country.[37] Barbados has led the way for other CCCCC member states in implementation of climate change adaptation since the Barbados Program of Action for SIDS (1994). The Barbados Coastal Zone Management Unit has been conserving its coral ecosystems and managing coastal areas from erosion and habitat loss since 1996. Currently, it is developing a coastal zone management plan with support from the Inter-American Development Bank that incorporates ecosystem-based climate change adaptation.

In sum, (i) CCRIF has estimated the cost effectiveness of adaptation options across the Caribbean; (ii) reef and mangrove restoration were among the most cost effective measures for adaptation; and (iii) CARICOM nations have used this and other research to frame their climate change adaptation strategies.

Case Study 6: Dominican Republic Climate Adaptation Action Plan: The Dominican Republic is highly vulnerable to the impacts of climate change, specifically sea-level rise, higher temperatures, and increased precipitation variability. The Dominican Republic developed its NAPA in 2008, emphasizing three priority sectors: agriculture and food security, water, and coastal-marine resources. The NAPA proposed numerous adaptation options, including coastal defenses aimed at the reduction of the coastal impacts of climate change (repair and reconstruction of tourism infrastructure and beach damages) and indirect associated impacts (reduction of hotel capacity, vector-borne diseases, negative spillovers to other sectors, and unemployment). The NAPA also proposed to develop coastal management plans that include reef restoration and afforestation, as well as the development of wetland and mangrove best practices to meet coastal defense and conservation objectives.

In sum, the Dominican Republic's National Adaptation Program of Action (NAPA) proposes coastal habitats as a coastal defense alternative, specifically through reef restoration and the development of wetland and mangrove best practices.

d. Habitat restoration

In most cases, the restoration of habitats for coastal protection benefits was motivated first and foremost by risk reduction considerations and secondarily by conservation considerations

[37] For example, "Climate Change and the Caribbean: Regional Framework for Achieving Development Resilient to Climate Change 2009–2015" and "Delivering Transformational Change 2011–2021: Implementing the CARICOM Regional Framework for Achieving Development Resilient to Climate Change 2011–2021."

(Table 6.1). In a few cases, projects were motivated first by conservation and secondarily by risk reduction considerations. These projects were clearly different from the infrastructure projects in (b) in that they were ecological restoration projects that sought also to enhance the delivery of coastal protection ecosystem services.

Case Study 7: Community-Based Mangrove Restoration in Gujarat, India: The state of Gujarat has the largest mangrove cover along India's western coastline, but it has been extensively degraded from natural and human causes. The State Forest Department and the Gujarat Ecology Commission implemented a mangrove restoration project with financial support from the India-Canada Environment Facility. The project focused on community-based restoration initiatives and promoted a multiple-stakeholder mangrove restoration exercise. In addition to enhancing mangrove cover, among the key objectives were the following: (i) to contribute to increased understanding and acceptance of the need for local communities, institutions, and industries to protect, conserve, and enhance mangroves; (ii) to enrich marine and coastal biodiversity; and (iii) to encourage public participation in an eco-development program for coastal villages and communities.

The targeted beneficiaries of the program are local fishing communities, marginal laborers, and local industries. The program requires participating industries to plant mangroves and allocate a specific area of coastal land for natural mangrove development. The reforestation exercise resulted in a total of 8,326 hectares of new mangrove cover. A study of 227 households found a variety of direct and indirect benefits accrued as a result of the reforestation exercise (Table 6.4). For instance, there were reported gains in fisheries income in 34 households and reduced cyclone and storm damages after mangrove planting in 74 households. As an indirect benefit, 54

Table 6.4: Mangrove and the Multiple Community Benefits (adapted from Viswanathan 2013)

Beneficial Outcome of Mangrove Restoration	Units	Reported No. of Units (227 households surveyed)
Annual average earnings from mangrove planting work	Indian Rupees	8735
Percent gain in fishery income after mangrove planting	Percent of households	31.5
Households extracting mangroves for use	Percent of households	45.8
Mangrove extraction for fodder	Percent of households	64.3
Mangrove extraction for fuel	Percent of households	35.7
Reduction of salinity ingress in crop lands	Percent of households	55.4
Reduction of crop damage because of winds	Percent of households	50.1
Reduction of effects of cyclones	Percent of households	73.6

households reported an increase in the employment of women from the program. Major challenges to sustaining such a program include development of institutional mechanisms to protect existing mangroves and determining the stakes and responsibilities of industries operating in the coastal zone.

In sum, (i) the Gujarat State Government with other partners initiated a community-based mangrove restoration program along the Gulf of Kuchch; (ii) principal beneficiaries and participants were local villages, laborers, and fishing communities; and (iii) the eco-development program resulted in 8,326 hectares of new coastal mangroves that provided increased coastal protection and other benefits.

e. Post disaster recovery and restoration

There are a few examples where post-storm actions have included re-examination of coastal management policies and direct support for coastal habitat restoration efforts (Table 6.1).

Case Study 8: Post-Typhoon Haiyan: Typhoon Haiyan, known as Typhoon Yolanda in the Philippines, was one of the strongest and deadliest storms in the history of the Philippines. The storm in November 2013, displaced millions and killed more than 6,000 people. Typically, around 20 typhoons hit the Philippines each year, with an increasing number in the super-typhoon category, such as Typhoon Haiyan.

Local communities—and many scientists—believe that the past destruction of mangroves contributed to the devastation brought on by the storm. Immediately following the typhoon, the Department of Environment and Natural Resources (DENR) announced a plan to spend around $8 million to restore mangroves and beach forests along the coasts of Leyte and Samar (Eastern Visayas region), the two islands that suffered the most damage from Haiyan. The majority of the funds will pay residents who help with the reforestation in a cash-for-work program.[38] As of August 2014, approximately $840,000 has been budgeted to cover mangrove planting on 9,800 hectares in this region, and work has already been completed on 600 of these hectares.[39]

The government of the Philippines had previously adopted a flagship program to grow 1.5 billion new trees on public lands throughout the country by 2016. The National Greening Program, which focuses on inland forests as well as mangroves and beach forests, was established through Executive Order 26 in 2011 with the goal of "poverty reduction, food security, biodiversity conservation, and climate change mitigation and adaptation" (DENR 2011). Noting that mangroves have been proven as buffer zones and protection in typhoon-affected regions, the DENR established the coastal forest rehabilitation program in the Eastern Visayas on top of the National Greening Program.[40]

There has been significant concern about the mangrove rehabilitation program. A four-month scientific assessment of damaged mangroves and beach forest post typhoon revealed that some of the mangroves that were intact before the storm only suffered minimal damage and are recovering, and some were not damaged at all. Some of the mangrove planting to meet social goals was having impacts on areas of natural ecological recovery, which were being

[38] http://blogs.wsj.com/searealtime/2013/11/28/philippines-plans-mangrove-forest-to-protect-coasts-from-storms/; http://www.denr.gov.ph/news-and-features/latest-news/1604-denr-sets-aside-p347m-for-coastal-forest-rehabilitation-in-eastern-visayas.html.

[39] http://www.mb.com.ph/mangroves-rehabilitation-project-in-full-swing/.

[40] http://www.mb.com.ph/denr-8-starts-p1-b-mangrove-rehab-project/.

trampled, and mangroves were being planted in novel areas (for example, in seagrass beds). Ecologists urged the national government to focus some efforts on ground surveys to determine areas where there was a need for planting, establishment of coastal greenbelts, reversion of abandoned fishponds to mangroves, and resettlement of coastal communities.[41] According to the DENR, recent restoration efforts in the Leyte Gulf have implemented better scientifically-informed techniques.[42]

In sum, after Typhoon Haiyan the Philippines (i) planned to spend $8 million dollars on mangrove restoration; (ii) an existing national program served as precedent for a cash-for-work planting program; and (iii) scientists stressed the need for better guidelines for planting and avoiding damage to naturally growing mangroves.

6.6| Discussion

The coastal protection benefits of mangroves and reefs have been influential in policy and practice in many locations across the globe (Table 6.1). There are clear examples over several decades where these perceived and measured benefits have led to significant conservation and restoration, as well as changes in coastal policies. These examples range from the national to the local scales, and cover at least five major types of actions, including habitat restoration, post-disaster recovery, and coastal zone management policies.

Most direct restoration projects are for mangroves and they are usually designed to meet multiple benefits. The most common examples are designed for disaster risk-reduction goals, but also meet conservation goals (for example, Vietnam and the Philippines, Table 6.1). At the same time, a growing number of ecological restoration projects are planned for coastal protection goals, as well. For example, NOAA increasingly evaluates its ecological restoration efforts based on the multiple benefits, including coastal protection benefits and job creation (Edwards et al. 2013, NOAA SAB 2014).

Many other countries, such as India, are clearly considering mangroves as bioshields for coastal protection,[43] although few projects have yet been implemented.[44] Key scientists and foundations in the country are pushing for more aggressive change and developing toolkits for mangrove restoration for coastal protection (Selvam et al. 2005).

The focus of this review was on case studies with direct links to decisions in policy and practice. It is likely that there have been many more indirect influences on policy and practice. The wealth of science and case studies, particularly on the coastal protection values and benefits of mangroves, is almost certainly having wide-ranging impacts. For example, past published coastal protection work is clearly cited in efforts to influence policy (for example, see Senator Aquino's letter for the Philippine's Greenbelt Bill, Appendix 6.1).

A better understanding of how to model coastal protection services in-depth can help decision makers make more cost-effective investments within sites (for example, ports). Narayan (2009) identified that mangrove islands were an under recognized part of effective protection for the Dhamra Port in India. He used standard coastal engineering models to examine how

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41 http://www.mindanews.com/top-stories/2014/04/04/p1-b-budget-for-mangrove-planting-in-leyte-samar-too-much-says-expert/.

42 http://www.mb.com.ph/mangroves-rehabilitation-project-in-full-swing/.

43 http://articles.economictimes.indiatimes.com/2011-03-18/news/29141776_1_coastal-areas-mangrove-nuclear-power.

44 http://www.ipsnews.net/2012/12/bioshields-best-defence-against-disasters/.

these benefits might be expanded effectively. Better valuations of their services (coastal protection, fisheries, and tourism) can influence many land and sea-use decisions. For example, Barbier et al. (2008) showed that leaving mangroves intact would deliver ten times more value in terms of coastal protection, fisheries, and forest harvest services (for example, fuel wood or honey), than cutting mangroves for aquaculture alone.

At national scales, it is also possible to assess risk with and without the presence of coastal habitats, and these assessments should help inform decisions about where to conserve and restore critical habitats. Arkema et al. (2013) identified qualitatively the variation in coastal protection services from reefs, mangroves, and other coastal habitats along the entire U.S. coastline. They showed that understanding this variation in coastal protection services can help identify national-scale conservation priorities for effective risk reduction, and these have informed the development of national-scale decision support tools.

6.7| Conclusions

From the review of the policies and projects in this and prior chapters, there are clear lessons learned and opportunities for expanding the practice and policy of natural coastal protection. There are direct ties as noted below between the lessons learned and future opportunities and needs.

There are a number of important triggers for policy change that have supported the use of natural coastal protection including:

i. Local knowledge and demand for coastal protection, particularly from mangroves
ii. Demand for other benefits such as food security and jobs with natural coastal protection as an ancillary benefit
iii. Clear evidence in ecology, economics, and engineering of benefits and cost effectiveness of mangroves and reefs for coastal protection;
iv. International legal obligations and funding, particularly for climate adaptation
v. Post-disaster rebuilding and restoration decisions that achieve multiple benefits for example, natural defense, conservation, and jobs).

Lessons learned

- There are now **decades of decisions supporting the conservation and restoration of mangroves and reefs for coastal protection.**
- **Economics matter, but local observations can be paramount.** Many early mangrove conservation and restoration efforts were motivated more by observations of habitat loss and flooding risk than by quantitative scientific or economic data.
- **Subsequent cost-benefit analyses show mangrove restoration** to be cost effective for risk reduction and these studies have been increasingly influential.
- **Values of coastal protection will be highest where reefs and mangroves are in front of significant infrastructure.** Cost-benefit estimates and valuations can widely vary, which is mainly related to the value of coastal assets behind reefs and mangroves.
- **Mangrove restoration for coastal protection is now a well-established practice**. The practice can be done well over hundreds to thousands of hectares of coastline, although challenges remain.

- **Restored mangroves and reefs will cause shoreline evolution (for example, Guyana).** Indeed the point from a coastal protection perspective often is to cause changes in erosion and sedimentation, which create land growth.
- **Mangroves and reefs should not be planted in "novel" areas.** If reefs and mangroves did not previously occur in an area, they likely will not survive there now. Poorly conceived projects fail to meet goals, can create hazards, and make it harder to execute well designed projects later.
- **Coral restoration for coastal protection is much less well established**; the numerous past coral restoration efforts were primarily designed to enhance fish production and recreation.
- **Teaming natural and artificial defenses can be very effective,** such as mangroves in front of dikes (which was done in Vietnam).
- **It is not yet common practice to use coral reefs and mangroves for coastal protection.** Even when analyses show that they can be used cost effectively for risk reduction, restoration may not be chosen because it is relatively novel practice compared to hard engineering (for example, Fiji).
- Numerous **National Adaptation Programs of Action** for coastal countries did not obviously prioritize natural habitats for coastal protection benefits, while those **for small island developing states often did prioritize natural coastal protection**.
- **Significant land use and funding decisions are made post-disaster** and these can support reef and mangrove restoration (for example, the Philippines).

Needs and Opportunities

- **Many well designed risk reduction plans, strategies, and programs are often not implemented**. Vietnam and the Philippines stand in stark contrast, as they are proactively restoring mangrove habitats at scale.
- **The mapping of key decision pathways is critical** to inform the science that is needed and in moving from plans to action.
- **It is critical to mainstream natural coastal defenses into national development and resilience strategies** to move from plans to action.
- **More demonstration projects are needed to help identify when and where nature-based projects provide benefits.** Societies have not reached a tipping point even for mangroves, where these projects are common practice.
- **Coastal planners and managers need better guidelines for siting and managing nature-based coastal defenses**.
- **Post-project monitoring and evaluations are essential** to gauge protection services, habitat quality, and maintenance costs.
- **There is an unmet need to model and measure erosion reduction values.** Erosion reduction and land building are valued for artificial defenses but are not generally valued for natural defense.
- **Transparency matters in projects.** Some reef restoration projects were excluded for lack of information on costs, approaches, and results.
- The **lack of stakeholder awareness** on the effects of reef degradation on current erosion and flooding **likely impedes support for coral reef restoration**.
- **Too few hydrodynamic (engineering) models account for nature-based defenses.**

6.8| References

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Appendix 6.1

Senate
Office of the Secretary

SIXTEENTH CONGRESS OF THE REPUBLIC)
OF THE PHILIPPINES)
First Regular Session)

'14 MAR 26 P4 :33

SENATE
S.B. No. 2179

RECEIVED BY:

Introduced by: Senator Paolo Benigno"Bam"A. Aquino IV

EXPLANATORY NOTE

Last year, super-typhoon Yolanda (Haiyan) hit Eastern Visayas and left thousands of people dead. Millions more became homeless and now, are struggling to cope with the loss of loved ones, life savings and livelihood.

Previous storms, Ondoy, Pablo and Sendong have wrought havoc to other cities and provinces in the past half decade, crippling the economic and social development of the Filipino people. The Philippines is battered by more than 20 typhoons a year, with an increasing number in the super typhoon category. These could bring as much damage as Yolanda. The losses attributed were caused by storm surges and strong winds coming from the open ocean. In the age of global climate change, this has unfortunately become the new normal.

The poor coastal communities' natural exposure to storm surges and lack of resources for preparation and recovery make them most vulnerable.

It is imperative to think of innovative, sustainable and cost-efficient ways for Filipinos to protect themselves, their properties and communities from the devastating impacts of natural disasters.

The Philippines is taking great strides in disaster preparedness. Recent laws created the Climate Change Commission (R.A. No. 9729) and strengthened the National Disaster Risk Reduction and Management Council (R.A. No. 10121). In addition, the People's Survival Fund (R.A. No. 10174) was created to support adaptation activities of local governments and communities to increase their resilience.

Disaster preparedness comprises a whole suite of items, such as early warning systems, elevated shelters, hard engineering (e.g., breakwaters) and green engineering/infrastructure.

An establishment of greenbelts of mangroves and beach forestsalong coastlines is a proven green engineering intervention. As the Philippines' 36,000 km coastline is among the longest in the world, coastal greenbeltseffectively mitigate the damaging impacts of waves and storm surges. Some of the scientifically proven benefits are:

- Wave height of wind and swell waves can be reduced by 13-66% over 100m of mangroves;
- Storm surge attenuation of 5-50 cm. per kilometer width of mangroves;
- Surface wind waves can be reduced by more than 75% over one kilometer of mangroves;
- 50% reduction in storm surges by a 7-km band of mangroves.

Furthermore, coastal forests can reduce the force, depth and velocity of a tsunami, lessening damage to property and reducing loss of life.
Coastal greenbelts are also cost-effective for disaster preparedness in the long term. The total valuation of mangroves is estimated at US$14,000-16,000 per hectare, of which about 80% is for coastal protection value. The cost of establishing coastal greenbelts to protect against storm surge and tsunamiwould only be a fraction of the damages that could be brought by the yearly battering of typhoons.

A number of existing laws, policies and regulations on mangroves have been issued over the years resulting in a fragmented and conflicting policy environment. This bill aims to come up with a strategic program to rationalize the development of mangroves and beach forests for coastal protection; it is anchored on a comprehensive policy framework that addresses the fragmented approach in the past.

Establishing the National Coastal Greenbelt Program shall provide the agency mandates, funding, and general guiding principles for implementing a science-based and cost-effective program. The proposed National Greenbelt Program mandates establishment of 100-meter protection zones, initially for the Eastern Pacific seaboard, where typhoons make landfall This Program can also reap added benefits.The establishment of science-based coastal greenbelts is expected to protect biodiversity, improve fisheries productivity, and enhance the tourism and livelihood potential of the area. Transforming vulnerable coastal villages into highly resilient and sustainable communities is a step towards a nation that is inclusive for all.

In view of the foregoing, the approval of this bill is earnestly sought.

Bam Aquino

Paolo Benigno A. Aquino IV

7| Recommendations

Mangroves and reef can offer many coastal protection benefits. There are good approaches for valuing these benefits and examples of how these approaches have been used in decision making. A number of key recommendations can advance the valuation of these benefits and their use in national accounting and other decisions. The following recommendations were developed from the science and policy reviews (chapters 2 to 6) and input from 20 plus experts who reviewed the work and participated in a review and synthesis workshop convened December 3–5, 2014. The recommendations identify the critical needs and opportunities in (i) data, (ii) models and methods, (iii) building support, and (iv) actions for advancing the assessment and the incorporation of coastal protection values from coral reefs and mangroves into making decisions. These recommendations are synthetic and targeted to decision makers.

7.1| The Evidence Base and Data Gaps

Field measures, models, and demonstration projects provide strong evidence of the coastal protection benefits of mangroves and reefs. Therefore, information per se is not the greatest constraining factor in better uptake of the coastal protection role of mangroves and reefs, but quite often the lack of direct experience by practitioners and decision makers seems to most limit uptake.

- **Coral reefs and mangrove forests should no longer be considered to be a "novel" way to defend the coast.** As offshore breakwaters, the basic engineering models of how reefs provide coastal protection are well known. Engineering demonstrations and models of the role of vegetation in flood and erosion reduction have been in use for decades.
- **The most important data gap in more accurately estimating reef coastal protection services is nearshore bathymetry,** particularly near the reef crest. This is a critical and general gap for understanding coastal processes, flood risks, and erosion along many tropical coastlines. Greater emphasis should be focused on collecting this data using a variety of approaches, including depth sounding, side-scan sonar, imagery inference (such as SeaWifs), and Lidar.
- **The most important gaps in estimating mangrove coastal protection services are forest density and structure,** which are used to estimate friction values in engineering models**.** The distribution and nearshore bathymetry is better detailed for mangroves, because they are intertidal.
- **Additional targeted projects are necessary to demonstrate how restored habitats can provide the most coastal protection benefits (that is, advance the practice of restoration for coastal protection).** There are a growing number of demonstration projects, including mangrove restoration projects, at significant scale. Yet the projects have failed to reach a tipping point in influencing policy, even for mangroves habitats. Very few projects explicitly restore reefs for coastal protection benefits.
- While information on engineering effectiveness is fairly well studied, **information on the economic value of coastal habitat protection services is partly limited by the small number of studies currently available and by their restricted geographic coverage**. This general lack of economic information restricts valuations of protection services. More studies are needed. It would be particularly useful to implement the modeling and EDF valuation approaches identified in this guidance note in a country where there are historical data to test and validate the models, such as the Philippines.

- **A perceived benefit of natural protection is lowered maintenance costs** because coastal habitats have the ability for self-repair and growth with sea-level rise. These benefits need to be measured more directly.
- **In some cases, the biggest limiting factor in estimating coastal protection benefits is socioeconomic data (for example, on asset values).** These values are central to many accounting problems, but can be surprisingly limited. Furthermore, to fully estimate coastal protection benefits for natural and artificial structures there needs to be better predictive models of future socioeconomic growth, similar to those done for future climate predictions.

7.2| Models and Methods

- **The modeling framework for estimating coastal protection benefits of habitats is clear (see Figure 4.2)** and can follow well-known, existing approaches (for example, from coastal engineering, insurance, and the Economics of Climate Adaptation) for estimating benefits and cost effectiveness of other coastal infrastructure. Models exist that can be used at two major scales: (i) local or site-specific models that can be highly quantitative (including numerical) models, and (ii) national, regional, and global models.
- **Existing hydrodynamic can be advanced to more easily account for nature-based defenses.** The modeling of reefs for coastal protection is very similar to that for breakwaters (and thus it is comparatively easy to extend existing tools, models, and parameters to account for reefs). However, the models and their parameterization for vegetated habitats (for example, mangroves and marshes) need to be more readily available. While complex models are needed for many circumstances, it would help if there were simpler models that could be more readily used by local practitioners (even if only for qualitative risk and coastal protection estimates).
- **The Expected Damage Function (EDF) approach is recommended for valuing coastal protection benefits**. Caution should be applied when using replacement cost valuation to ensure it meets the necessary criteria, since the approach tends to overestimate values of coastal protection. But replacement cost valuation is recognized as a second best, and often easily implemented, approach, if it is not possible to do an EDF approach.
- **Purpose-specific models should be built for estimating the coastal protection benefits of mangroves and coral reefs.** These models should cover cross-shore and longshore protection services. These purpose-specific models will better serve site-specific projects aimed at habitat conservation or restoration for coastal protection.
- **Surge-reduction models for mangroves can be advanced**. Mangroves can play a critical role in storm surge reduction. However, better parameterization of the relationships between vegetation characteristics and friction is needed and this can be achieved through (i) simplified solutions for idealized geometries of mangrove trees and roots or (ii) numerically derived estimates for more complex modeling.
- **General ecosystem service models and tools could help in evaluating coastal protection benefits** by developing more robust and standardized valuation methods from a wider geographic footprint. The present valuations and economic assessments are limited in context and geography (for example, most estimates of mangrove values are from rural environments).
- **Pilot projects are needed that incorporate coastal protection services into natural capital accounting.** These projects should follow the approach in the UN Statistical Division (UNSD 2013) System of Environmental-Economic Accounting/Experimental Ecosystem Accounting

(SEEA/EEA). There are a number of issues that pilot projects should consider, such as developing estimates of future service flows and their valuation over time. However, such issues as Basic Spatial Units (BSU) and Land Cover/Ecosystem Functional Units (LCEU) may be very straightforward to develop for protective services of reefs and mangroves (see Chapter 5).

- **For mangroves and reefs (and natural defenses in general), better modeling and measuring of erosion reduction values is needed.** Although erosion reduction (and land building) is an important benefit from reefs and mangroves, it is not generally valued as a natural defense. The causes of erosion can be very localized and difficult to assess, making it hard to develop clear and general relationships between habitats and coastal erosion.

7.3| Building Public and Governmental Support

It is critical to bring natural coastal defenses into national development, coastal management, climate adaptation, disaster risk management, and resilience plans. To do so will require the development of public support and political will.

- **Many well designed risk reduction plans, strategies, and programs are often not implemented and this needs to change**. This guidance note identified many adaptation and coastal zone management plans that considered natural coastal protection benefits that have not been implemented. Vietnam and the Philippines stand in stark contrast as they are proactively restoring mangrove habitats at scale.
- **Many countries need to develop national coastal risk maps.** This is a critical first step for overall risk reduction and nature-based coastal protection. Many countries are moving toward developing these maps, creating opportunities to include natural protection benefits in planning.
- **These national risk maps should identify where and how much risk reduction value is currently provided by reefs and mangroves.** The critical point of such maps is to demonstrate the variation in coastal protection (that is, where reefs and mangroves offer some of the greatest values in national coastal protection). These maps would also prioritize where coastal habitat protection and restoration offer the greatest risk reduction benefits.
- **The lack of stakeholder awareness likely impedes coral reef restoration.** Because coral reefs are below the surface, it is difficult for stakeholders to see reef degradation and connect it to above water changes in erosion and flooding. Yet it is well known from coastal engineering that small degradations in the height of offshore breakwaters can have huge impacts on erosion and flooding.
- **A better accounting of the roles that reefs have played in coastal protection is needed to build awareness of their benefits.** The study of past impacts offers one pathway. It is important to monitor the recovery of coral reefs and changes in flooding and erosion after major disruptions to understand the relationship between reefs and coastal protection benefits. For example, the global coral bleaching in 1998 offered opportunities to study such changes.
- **There is value in estimating coastal protection benefits at both local and national levels.** The types of decisions and decision makers are often quite different at these levels.
- **Specific projects for risk reduction and climate adaptation should be implemented locally and must be designed for local conditions**. National mapping will help to focus, identify, and provide priorities for national decisions, but cannot replace the need to design projects locally.

7.4| Actions to Sustain and Enhance the Coastal Protection Value of Coral Reefs and Mangroves

- **Reducing threats to mangroves and coral reefs and improving their management offer the most cost-effective solutions to retaining their coastal protection services.**
- **Reefs and mangroves should be restored for their coastal protection benefits.** Restoration has been shown to be cost effective for coastal protection in comparison to other approaches, such as submerged breakwaters. However, restoration should not be used to create "novel" habitats, that is, putting mangrove or reef-like structures in areas where they did not previously exist.
- **Mangrove and reef coastal protection projects should be designed to measure and value socioeconomic benefits** and, in particular, to inform national ecosystem accounting.
- **Guidelines and best practices for restoration of mangroves and reefs for coastal protection should be advanced.** The body of guidance on mangrove restoration is growing and while it is very good, it can still be enhanced. There is little guidance on best practices for reef restoration for coastal protection.
- **New, large-scale commitments to restore degraded mangroves and coral reefs should be developed**. Restoration efforts in Vietnam have shown that the amount (hectares) of mangrove conservation and restoration can be brought to the same scale as the past loss of these habitats. Few (if any) other countries have made such commitments.
- **Better measures for coastal protection benefits are needed to attract innovative and sustainable financing** through mechanisms such as climate bonds, blue infrastructure bonds, green adaptation funds, and insurance that accounts for protection benefits**.**
- **More developing nations should include reefs and mangroves in their national adaptation plans.**
- **More developed nations should incorporate coral reef and mangrove management and restoration in to their support programs for adaptation and risk reduction (for example, in green adaptation funds).**

Wealth Accounting and the Valuation of Ecosystem Services

Wealth Accounting and the Valuation of Ecosystem Services (WAVES) is a global partnership led by the World Bank that aims to promote sustainable development by ensuring that natural resources are mainstreamed in development planning and national economic accounts.

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