The Value of Turneffe Atoll Mangrove Forests, Seagrass Beds and Coral Reefs in Protecting Belize City from Storms

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The Value of Turneffe Atoll Mangrove Forests, Seagrass Beds and Coral Reefs for Shoreline Protection in Belize

Turneffe Atoll plays a vital part in Belize's marine ecosystem and economy. Not only is it home to world-class sport fishing, diving and eco-tourism, a large portion of the country's commercial lobster and conch fisheries are located there. Beyond these direct recreational and commercial benefits, the extensive coral reefs, mangrove forests, and seagrass beds support an array of indirect ecological and economic services to central Belize. Moreover, Turneffe Atoll is the principal marine structure east of Belize City that provides direct protection from waves, flooding and shoreline erosion associated with storms and hurricanes.

Ecosystem Services Provided by Coral Reefs, Mangrove Forests and Seagrass Beds

Interest in the value of mangrove forests, seagrass beds and coral reefs has been growing since first becoming systematically studied over two decades ago (Costanza et al. 2017). Our understanding has grown from a simple recognition that these unique coastal natural resources provide protection from storms and nursery areas for fisheries to a deeper recognition of the complex set of ecosystem services providing extensive direct and indirect contributions to the social and economic health of shoreline communities. With over one-third of the world's population living in the coastal zone, these ecosystems are some of the most threatened globally (Lotze et al. 2006; Worm et al. 2006). Their historical decline is well documented, but their social and economic importance is just beginning to emerge (Barbier et al. 2011). Further complicating the landscape, there is now sufficient evidence to suggest that some ecosystem services, such as coastal protection and habitat-fishery linkages, are not uniform across a coastal seascape (Bierbaum 2009).

Communities and economies of coastal Belize and other Caribbean countries are highly dependent upon the ecosystem services provided by mangrove forests, coral reefs and seagrass beds (Table 1). Ecosystem services are the ecological characteristics, functions, or processes that directly or indirectly contribute to human well-being (Costanza et al. 1997; Millennium Ecosystem Assessment 2005). The growing understanding of the value of these ecosystem services has fostered an increased interest by governments, such as Belize and other countries, to include them in their coastal planning (CZMAI 2016). Issues relating to the destruction of mangrove forests, coral bleaching and decline, seagrass decline, climate change, and sea level rise has fueled this focus on the value of coastal resources and on how they contribute a country's social and economic well-being.

Mangrove forests protect inland communities and freshwater resources from saltwater intrusion (Semesi 1998; Badola and Hussain 2005). The root systems of mangroves prevent the resuspension of sediment and slow water flow in areas where the protection of shoreline-based activities are important (Gilbert and Janssen 1998). Mangroves not only protect areas from storms, they have recreational and fisheries service value as well (Aburto-Oropeza et al. 2008). In general, mangroves serve as natural barriers to protect life, infrastructure, and property of coastal communities (Badola and Hussain 2005). Additionally, the protection of infrastructure and property will indirectly benefit the tourism and recreational industries. Valuation of mangroves has primarily focused on their storm protection services. Research on major storm impacts has shown that coastal communities experienced greater damage and higher mortality rates from many types of natural disasters when mangroves had been removed (Danielson et al. 2005; Das and Vincent 2009).

Table 1: Ecosystem services provided by coral reefs, mangrove forests and seagrass beds

Ecosystem Services	Coral Reefs	Mangroves	Seagrass Beds
Raw materials and food	X	X	
Shoreline protection	X	X	X
Fisheries maintenance	X	X	X
Nutrient recycling			X
Tourism, recreation, education, research	X	X	X
Erosion control		X	X
Water purification		X	X
Carbon sequestration/climate regulation		X	X

Coral reefs and mangroves minimize the impact of storms by reducing wind action, wave action, and currents. Coral reef structures also buffer shorelines against waves, storms, and floods (Moberg and Folke 1999; Adger et al. 2005). In general, the structure of coral reefs provides a significant barrier to storm surges (UNEP-WCMC 2006). They are increasingly under human and climatic threat due to water pollution, sea temperature rise, and ocean acidification (Bruno and Bertness 2001). Further, regional studies have shown that the threats that coral reefs are facing affect their ability to provide ecosystem services (Bruno and Selig 2007). Coral reefs generally are under-valued because the ecosystem service of storm protection is an indirect benefit, and as a result, often overlooked in policy and decision making contexts (Brander et al. 2007). Some economic studies of coral reefs have included their diverse uses, which include direct uses such as fishing and diving, in addition to indirect uses such as storm protection.

Seagrasses are flowering plants that colonize shallow marine and estuarine habitats. With only one exception (the genus Phyllospadix), seagrasses colonize soft substrates (e.g., mud, sand, cobble) and grow to depths where approximately 11% of surface light reaches the bottom (Duarte 1991). Seagrasses prefer wave-sheltered conditions as sediments disturbed by currents and/or waves lead to patchy beds or their absence (Koch et al. 2006). Despite being among the most productive ecosystems on the planet, fulfilling a key role in the coastal zone (Duarte 2002) and being lost at an alarming rate (Orth et al. 2006, Waycott et al. 2009), seagrasses receive little attention when compared to other coastal ecosystems (Duarte et al. 2008).

Coastal protection and erosion control are often listed as important ecosystem services provided by seagrasses (Hemminga and Duarte 2000, Spalding et al. 2003, Koch et al. 2009). Seagrass beds protect the shoreline by attenuating strong waves, as well as stabilizing sediment. By reducing wave height, current velocities and sediment resuspension, seagrass meadows protect shorelines from erosion. Seagrasses help trap fine sediments and particles suspended in the water column, which increases water clarity (Fonseca and Cahalan 1992, Koch 1996, Prager and Halley 1999). When a sea floor area lacks seagrass communities, the sediments are more frequently stirred by wind and waves, decreasing water clarity, affecting marine animal behavior, and generally decreasing the recreational quality of coastal areas. Seagrasses also work to filter nutrients that come from land-based industrial discharge and stormwater runoff before these nutrients are washed out to sea and effect other sensitive habitats such as coral reefs. Seagrasses also generate value as habitat for ecologically and economically important species such as scallops, shrimp, crabs, and juvenile fish. Seagrasses protect these species from predators and provide food in the form of leaves, detritus, and epiphytes.

In general, when coral reefs, mangrove forests and seagrass beds are destroyed or damaged, their absence has been shown to increase the damage to coastal communities from normal wave action and heighten damage from more violent storms. The storm protection that coastal ecosystems provide prevents both the loss of life and property for communities living in near-shore areas (Orth et al. 2006). It is particularly important to Caribbean countries where tropical storms and hurricanes occur with varying intensities and frequencies each year.

Measuring the Value of Shoreline Protection

Production function or bio-economic 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 generally well known.

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 traditional econometric 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.

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 mangroves mitigates the expected incidence of storm damage and thus, provides a benefit similar to an increase in income. Conversely, a loss in mangrove 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 (World Bank 2016).

Shoreline Protection Valuation Studies

This section reviews and discusses current literature on the economic valuation of ecosystems services from mangroves, seagrasses and coral reefs for coastal protective services. The basis for this literature review was provided in a World Bank (2016) report that examined coastal protection and many other ecosystem services. Several additional studies not contained in the World Bank review were also included. Unfortunately, none of the studies identified for this review examined the shoreline protection value of seagrass beds. 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 represented 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 percent 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. Therefore, although many regions were 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 study would need to consider the applicability of estimates, for example, from Southeast Asia for the Caribbean.

The studies that focus on coastal protection included 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. Other key valuation methods include the avoided damages method (11 estimates) and direct market pricing (eight estimates). The endpoints measured in each study vary but are often in dollars per distance or area (hectares) measured annually.

The terrestrial distance measure varied where some authors consider the elevation within which the flooding will occur, while others use a simple cut-off of distance from the coast regardless of elevation. The decision on how to determine the extent of the damages to consider and value is context specific, but authors often use rules of thumb, flat rates (that is, five 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 were met in the current context.

Table 2 summarizes shoreline protection values from eight studies conducted in Caribbean countries. Seven of the studies focused on coral reefs while one considered the protection vale of mangroves in combination with coral reefs. All of the studies reported the annual value of shoreline protection from coral reefs while two studies also provided “per area” values as well. The per area values point to a common problem when evaluating and comparing results – they are often reported in differing units. The protection value of a linear kilometer of coral reef or mangrove shoreline would provide a much different picture if the same reef or mangrove forest were measured in acres or hectares. The width of these two coastal resources greater wave attenuation and storm surge reduction effects as width increases. Further, different methodologies and models makes the application of results from one study to another problematic (World Bank 2016) as is shown below.

There is a wide range in annual shoreline protection values shown in Table 2. The smallest value was for a reef area in Bonaire. The coral reef in Bermuda accounted for $265 million (USD) in annual damages avoided. Burke and Maidens’ (2004) study estimated damages avoided by coral reefs for the entire Caribbean region was nearly $1.5 billion (USD). Their study also quantified the importance considering shoreline development level. Annual damages avoided for medium developed shoreline were three times greater than shoreline with low development levels. Damages avoided for highly developed shoreline were over ten times greater than shorelines with medium development. This study underscores the value of segmenting shorelines into discrete development level units which will help planners identify areas with the greatest economic risks and where reefs and mangroves provide the greatest benefits.

In the natural resource economics literature, the Expected Damage Function (EDF) approach was first applied to the economic valuation of coastal protection services provided by coastal wetlands (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.

Table 2: Shoreline protection valuation studies conducted in the Caribbean region					
Location	Country	Ecosystem	Annual Value ($US)	Average Value per Area	
Portland Bight MPA	Jamaica	Coral Reef & Mangroves	$336,000		Caesar et al. 2000
Montego Bay	Jamaica	Coral Reef	$65,000,000	$260,000/ac.	Gustavson 1998
Bermuda	Bermuda	Coral Reef	$265,900,000		
Bonaire Island	Bonaire	Coral Reef	$51,500		Van Zanten and Van Beukering 2012
Tobago	Tobago	Coral Reef	$25,500,000		Van Zanten and Van Beukering 2012
St. Lucia	St. Lucia	Coral Reef	$39,000,000		Burke et al. 2004
Coastline	Caribbean	Coral Reef	$1,475,000,000		Burke and Maidens 2004
Coastline (Low dev.)	Caribbean	Coral Reef		$11,000/km	Burke and Maidens 2004
Coastline (Med. dev.)	Caribbean	Coral Reef		$45,000/km	Burke and Maidens 2004
Coastline (High dev.)	Caribbean	Coral Reef		$550,000/km	Burke and Maidens 2004

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. 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, seagrasses 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 shoreline 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.

The Value of Shoreline Protection for Turneffe Atoll and Belize

Because of the diversity in methods employed and the way study results were presented (Table 2), it is difficult to use a benefits transfer approach for valuing Belize's shoreline protection services from coral reefs, mangrove forests and seagrass beds. The reason for this is that the results were presented as annual totals which do not allow for conversion to a per acre or hectare basis to make them amenable for transfer to other locations. However, two notable projects in Belize provide significant insight into the value of these coastal resources in avoiding storm damages. The two projects are related in that the data developed in the first study by Cooper et al. (2009) underpinned the advancement of the second project (CZMAI 2016).

World Resources Institute Project

In a study sponsored by the World Resources Institute's *Coastal Capital* project in the Caribbean, Cooper et al. (2009) undertook a detailed study of the economic contribution of coral reefs and mangroves in Belize. The economic valuation method replicated methods originally developed by the World Resources Institute (WRI) and Institute of Marine Affairs (IMA) in Trinidad and Tobago for application in the Eastern Caribbean. The study focused on the economic activity generated by coral reef- and mangrove-dependent tourism and fisheries. It also estimated the losses in coastal property value that would result if the protective function of these habitats declined. By limiting the study to these three services, the results underestimated total value of coral reefs and mangroves. Much of this work contributed to the development of Belize's Integrated Coastal Management Plan (CZMAI 2016) in subsequent years.

The WRI methodology Cooper et al. (2009) used for valuing shoreline protection was adapted to factor in the role of atolls and the offshore barrier reef in mitigating wave energy and to allow for the explicit evaluation of the roles of coral reefs and mangrove forests in protecting shorelines. This study used a modified avoided damages approach to estimate the value of shoreline protection services along segments of the Belize coastline protected by coral reefs and mangroves. The avoided damages approach involved estimating the likely economic losses (in property value) to a coastal area from a given storm event, both with and without the presence of reefs and mangroves present. The difference represents the "avoided damages" attributable to the presence of reefs and mangroves.

The approach developed by WRI and IMA involved geographic information system (GIS) and analytical modeling components in addition to an economic component. The adaptation of this methodology by Cooper et al. (2009) involved five steps:

- Identify land that is vulnerable to wave-induced erosion and storm damage.
- Identify coastline that is protected by coral reefs and mangroves.
- Estimate the relative stability of the shoreline based on a range of physical factors.
- Determine the share of shoreline stability attributed to coral reefs and mangroves.
- Estimate "damages avoided" due to the presence or absence of coral reefs or mangroves based on the value of property (land and built structures) in vulnerable land protected by coral reefs and mangroves.

Each of the five steps incorporated data from a variety of sources to populate model components. For example, vulnerable lands were estimated from storm surge and wave height data (based on a 25-year storm event), coastline shape, and land elevation. Coral reef and mangrove location and area was identified from government and non-governmental organization surveys and mapping and satellite data. Shoreline stability was measured by an index of seven physical factors including: coastal geomorphology, geology, coastal protection by structures (atolls or seawalls), coral reef index, hurricane frequency, coastal elevation, and coastal vegetation. Property values for land and built structures from 2007-08 were gathered through internet searches.

Under the definition of land vulnerable to wave-induced erosion and storm damage defined in Cooper et al. (2009) as any land within 1 km of the coast which has an elevation of 5 m or less, 693 km^2 of land was classified as vulnerable. This is 87% of the land within 1 km of the Belize coast. About 66% of the mainland coastline and 72% of the cayes were classified as protected by coral reefs (Table 3). The study estimated that there were between 400 and 420 km^2 of mangroves within 1 km of the coastline of Belize, including cayes, resulting in half of the mainland coast and 75% of the offshore islands being sheltered by mangroves. Both coral reefs and mangroves shelter over 35% of the mainland coast and 75% of the offshore islands.

Table 3: Extent of reef or mangrove protected shoreline

Location	Coastline length (km)	Reef Protected Coast (km)	Percent Protected by Reefs	Mangrove Protected Coast (km)	Percent Protected by Mangroves	Reef & Mangrove Protected Coast (km)	Percent Protected by Both
Mainland	518	342	66%	260	50%	189	37%
Offshore	1,288	928	72%	972	75%	690	54%
Total	1,805	1,270	70%	1,232	68%	879	49%

Source: Cooper et al. 2009, p. 16

The model used for the study showed that coral reefs contributed between 12% and 40% of the shoreline stability. The coral reef share was found to be very high along all of the cayes in the outlying atolls, such as Turneffe and along Ambergris Caye. Where mangroves were present, they contributed between 10% and 32% to shoreline stability.

Both undeveloped and developed coastal property values were collected from Internet searches during 2007 and 2008. Average land and built structure property values ranged from \$44 per ft^2 in San Pedro to \$32 for Caye Caulker and Placencia. Remote properties along the coastline averaged \$4 per ft^2. For each area mapped as “vulnerable” based on the 25-year storm event, the property value was combined with the degree of shoreline stability provided by coral reefs or mangroves for the nearest coastal segment to estimate potentially avoided damages. The sum of these values was then multiplied by 4% to reflect the probability of the 25-year storm event occurring in any given year.

From the model, potentially avoided damages through reduced erosion and storm damage from coral reefs in Belize was valued at $300 million annually (Table 4). Mangroves were estimated to contribute $278 million per year in potentially avoided damages. Together, coral reefs and mangroves provide shoreline protection services with an average annual value of $578 million. This equates to a value of about $8,300 per hectare per year.

Table 4: Damages avoided value of land protected by coral reefs and mangroves

	Land Protected		
	Hectares	$BZ/Ha	Annual Damages Avoided ($BZ)
Belize			
Coral Reefs	28,300	$10,601	$300,000,000
Mangrove Forest	41,000	$6,780	$278,000,000
Total	69,300	$8,341	$578,000,000

Source: Cooper et al. 2009; Annual Damages Avoided were converted from $US to $BZ

Belize Coastal Zone Management Plan

The Belize Integrated Coastal Zone Management Plan (CZMAI 2016) also used a bio-economic model to estimate the value of shoreline protection fostered by coral reefs, mangrove forests and seagrass beds. Plan development was undertaken through a partnership with the World Wildlife Fund and the World Resources Institute's *Natural Capital Project*. This collaboration brought together critical information about the benefits coastal and marine ecosystems provide for people and the impacts human activities have on them. The process involved a flexible work plan that made knowledge building, ecosystem services, and stakeholder engagement central to the process.

This information was mapped comprehensively for both the coastal and marine environs for the first time in Belize. Coastal Advisory Committees and other stakeholder groups in nine planning regions communicated their values and goals for marine and coastal management through meeting minutes, surveys, and interviews. With this information, CZMAI determined how to group marine and coastal uses into useful zoning categories that would be useful to government agencies and stakeholders to guide the implementation of the ICZM Plan. Zones included locations set aside for marine protected areas, as well as areas prioritized for fishing, coastal development, marine tourism, aquaculture, transportation, and other human uses. An important component of the plan was to document the location and characteristics of near-shore coral reef, mangrove forest and seagrass bed habitats and examine the shoreline protection services they provide.

Understanding the role that nearshore habitats play in the protection of coastal communities and resources is increasingly important in the face of a changing climate and growing development pressure. Belize's coastal planners employed the InVEST Coastal Protection Model that quantifies the protective benefits that natural habitats provide against erosion and inundation (flooding) in nearshore environments. The model uses shoreline and coastal resource characteristics to compute summaries of nearshore wave information and outputs the total water level and the amount of shoreline erosion in the presence and absence of nearshore marine habitats (e.g., coral reefs, seagrass beds and mangroves). Outputs can be used to better understand the relative contributions of different natural habitats in reducing nearshore wave energy levels and coastal erosion and to highlight the protective services offered by natural habitats to coastal populations.

The InVEST Coastal Protection model produces an estimate of wave attenuation and reduction in shoreline erosion provided by coastal and marine habitats based on the variables in Table 5. By running the model in the presence and absence of habitats or changing various characteristics of these ecosystems, such as fragmentation or areal extent, users can value coastal protection for people and property from storms and understand how coastal protection will change under different management scenarios. The model calculates the area and value of land protected by habitats during a single storm event. By incorporating the return period of the storm and avoided damages, the model quantifies the value of coastal protection provided over a user-defined time horizon and the average annual value of habitats for protection.

Table 5: Description of coastal protection input data for Belize

Input	Source	How the Data Were Used in the Model
Bathymetry	ASTER GDEM v2 – 30 meter resolution	Water depths were used in the wave model to quantify the effect of coastal habitats on wave attenuation and thus their ability to provide protection for coastal communities from storms.
Coral	CZMAI and Peter Mumbry	Barrier coral reefs are one of four habitat types in the coastal hazards index that determines exposure to erosion and flooding.
Mangrove	World Wildlife Fund	Mangrove forests are one of four habitat types in the coastal hazards index that determines exposure to erosion and flooding
Seagrass	CZMAI	Seagrass beds are one of four habitat types in the coastal hazards index that determines exposure to erosion and flooding
Seagrass and Mangrove Physical parameters	Literature survey (see InVEST Users Guide	These physical parameters (diameter, height, and density of seagrass stems and mangrove trunk, roots and canopy) determine the resistance of these habitats to waves and in turn quantify the ability of seagrass and mangroves to provide protection for coastal communities from storms.
Coral Reef Geometry	Extracted for discrete locations from Belizean coral reef profiles (Burke 1982).	The reef geometry (reef face slope, rim angle, depth at offshore edge, depth over reef top, and depth of reef top) all determine how much wave energy is dissipated by the reef and in turn the amount of protection provided by the reef for coastal communities from storms.
Category Hurricane and Surge Elevation for Each region	Storm Hazzard Assessment for Belize strongest category storm within a 10-year return period.	The increase in coastal water level due to wind and pressure gradients associated with storms allows waves to propagate further inland before breaking due to decreasing depth.
Starting Wave Conditions	Storm Hazzard Assessment for Belize; Coastal Engineering Manual	Offshore wave height and period. This is the starting wave which is propagated over the vegetated bathymetry profile to compute the wave height profile and erosion estimates.

	(2008); measured fetch wave lengths; average depths	
Human Population	Statistical Institute of Belize; Biodiversity and Environmental Resources Data System of Belize.	These data allow the assessment of where habitats are most critical for protecting people.
Property Value	World Resources Institute; Natural Capital Project	These data are used to quantify damages from storms and hurricanes and to value coastal protection services provided by habitats.

Source: CZMAI 2016; p. 224.

The model values of coral reefs, mangroves and seagrass for protection from a storm (i.e., avoided damages) by multiplying the areas of land protected for each segment by the average property value of developed and undeveloped land in each planning region. To quantify coastal protection provided between the present and 2025, avoided damages per storm event and the probability of a Category 1 hurricane occurring each year during this time horizon was used.

An additional protective role that habitats provide is the reduction of overland storm surge elevations and inundation owing to mangroves. Because of a lack of reliable topography data and modeling limitations, this reduction was omitted from the analysis. Consequently, the InVEST model likely over-estimates the amount of erosion in the presence of vegetation. Thus, mangroves probably provide more protection than estimated in the analysis, thus increasing damages avoided.

The InVEST Coastal Protection model estimated the area of coral reefs, mangrove forests and seagrass beds in Belize and for Turneffe Atoll (Table 6). The area of these resources totaled nearly 300,000 hectares or 3,000 km^2. Turneffe Atoll's portion was estimated to be about 47,000 hectares or 15.8% of the country's coral reef, mangrove and seagrass resources.

Table 6: Total area of coral reef, mangrove forest and seagrass beds in Belize and Turneffe Atoll

	Belize		Turneffe Atoll		
Coastal Resource	Hectares	Percent	Hectares	Percent	Percent Turneffe
Coral Reefs	29,692	9.9%	4,195	8.9%	14.1%
Mangrove Forest	75,192	25.2%	6,475	13.7%	8.6%
Seagrass Beds	193,623	64.9%	36,643	77.4%	18.9%
Total	298,507	100.0%	47,313	100.0%	15.8%

Source: CZMAI 2016

The amount of Belize coastal land protected by coral reefs, mangroves and seagrasses, including mainland and offshore cayes and atolls, slightly exceeds 35,000 hectares (Table 7).

These three coastal resources associated with Turneffe Atoll protect about 6,100 hectares or 17.5% of all lands protected. The Turneffe Atoll share of protected lands includes the cayes within the atoll as well as a portion of the mainland in the atoll's storm shadow.

The InVEST Coastal Protection model calculated the annual average damages avoided, due to coral reefs, mangroves and seagrasses, amounted to $3.5 billion for the entire country (Table 7). Turneffe Atoll accounts for 10.7% or $382.3 million of the damages avoided annually. By dividing the area of Land Protected into Annual Damages Avoided, a rough estimate of the value of protection services by each hectare of coral reefs, mangroves and seagrasses can be calculated. The difference in value per hectare between Turneffe Atoll and Belize can be attributed to the low development level on the atoll and the relatively small segment of the mainland coast protected by the atoll.

Table 7: Annual value of shoreline damages avoided by coral reefs, mangrove forests and seagrass beds by area of land protected

	Land Protected (Ha)	$BZ/Ha	Annual Damages Avoided ($BZ)
Turneffe Atoll	6,134	$62,326	$382,305,747
Belize	35,074	$101,433	$3,557,673,432

Source: CZMAI 2016

Another way to consider the value of coral reefs, mangroves and seagrasses is to calculate Damages Avoided per hectare of the resource (Table 8). The values for Belize and Turneffe Atoll show that each hectare of these three resources provides about $12,000 in damage avoidance for the country and $8,000 for Turneffe Atoll. The upshot of this data is that if the area of coral reefs, mangroves and seagrasses declines, each remaining hectare will become much more valuable for shoreline protection.

Table 8: Annual value of shoreline damages avoided by total area of coral reefs, mangroves, and seagrasses (CRMS)

	CRMS Size (Ha)	$BZ/Ha	Annual Damages Avoided ($BZ)
Turneffe Atoll	47,313	$8,080	$382,305,747
Belize	298,507	$11,918	$3,557,673,432

Source: CZMAI 2016

Summary of Other Economic Benefits from Coral Reefs, Mangrove Forests and Seagrass Beds

As noted earlier in this report, shoreline protection is only one of several ecosystem services provided by coral reefs, mangroves and seagrasses. Cooper et al. (2009) estimated that the economic contribution of coral reef and mangrove-associated tourism contributed about $345 million in gross revenues per year to the Belizean economy (Table 9). The Cooper study did not estimate tourism expenditures for Turneffe Atoll. However, based on the percentage of Belize's coral reef and mangrove resources (10.1%), an estimated $35 million in tourism expenditures would be associated with the atoll. In a separate study, Fedler (2011) estimated the value of marine tourism on Turneffe Atoll at nearly $84 million. The CZMAI estimate of tourism expenditures associated with coral reefs, mangroves and seagrasses was about $231 million with about $20 million occurring around Turneffe Atoll. Differences in methodologies across studies accounted for some of the differences in estimates for Turneffe Atoll and Belize. However, they all show that a substantial portion of tourism expenditures occur in the coastal margins of Belize with a very meaningful percentage occurring around Turneffe Atoll.

Table 9: Estimates of tourism expenditures and fishery values associated with coral reefs and mangroves

		Millions $BZ	
Source	Activity	Belize	Turneffe Atoll
Cooper et al. 2009	Tourism & Recreation	$345.6	$35.2[1]
Fedler 2011	Tourism & Recreation	--	$83.5[2]
CZMAI 2016	Tourism & Recreation	$231.2	$20.1
Cooper et al. 2009	Lobster Fishery	$18.9	$1.9
Fedler 2011	Lobster Fishery	$13.6	$1.0
CZMAI 2016	Lobster Fishery	$16.4	$1.6

[1] Estimate based on 10.1% of coral reefs and mangroves present on Turneffe Atoll.

[2] Based on tourism activity independent of coral reef and mangrove influence.

The lobster fishery is the most economically valuable in Belize. Each of the three studies estimated the value of the lobster fishery (Table 8). Though the data were from different years, the values were very consistent both for Belize and Turneffe Atoll. This finding is not surprising as the lobster harvest has been relatively consistent from year to year (Fedler 2011).

Discussion and Conclusions

The Belizean coastline is exposed to a number of storm hazards, such as flooding, wave attack and erosion that can make coastal communities especially vulnerable to disasters. These hazards are expected to continue or worsen as climate change and rising sea level increase these threats to coastal communities. Despite these risks, the coastal areas of Belize have continued with economic development and population growth.

Currently, the Central Region holds the largest proportion of Belize's population and has the greatest economic value. As a result, building community resilience to storm impacts by maintaining and improving natural protective systems should become a priority. Turneffe Atoll is the principal marine structure protecting Belize City and the central Belizean coast from storm and hurricane impacts. The atoll contains over one-sixth of the country's coral reef, mangrove forest and seagrass bed resources. Impairing the storm protection benefits of these resources by unregulated development, pollution and other factors will likely result in increased loss of life and property damage from future storm events. What is abundantly clear, from the literature and modeling undertaken by the CZMAI, is the unequivocal value of Turneffe Atoll's marine resources to the well-being of Belize's citizens and economy.

It is difficult to precisely estimate the value of ecosystem services in general, let alone for a specific service such as shoreline protection as the two examples above demonstrate. Each model used to estimate damages avoided, though similar, were based on different assumptions, used disparate data, and calculated benefits under different storm frequencies and strengths. For example, Cooper et al. (2009) estimated that coral reefs and mangroves protected nearly 70,000 Ha of the Belize shoreline, while the Belize Integrated Coastal Zone Management Plan (ICZMP) identified 35,000 Ha of land being protected (CZMAI 2016). Further, Cooper et al. (2009) based their avoided damage values on a 15-year storm event whereas the ICZMP estimates were based on the frequency of a Category 1 hurricane occurring within 10 years. These hurricanes typically have a 72% chance of occurring within 10 years. Other factors, such as the year and method property values were determined and whether or not storm surge was included in the model, can also substantially affect estimates of damages avoided.

Comparing the annual damages avoided values from the two studies showed that the InVEST model used in the ICZMP were an order of magnitude greater than those in the Cooper et al. (2009) study. For the entire country, annual damages avoided from the Cooper study totaled $578 million compared to $3.5 billion estimated in the ICZMP. For Turneffe Atoll, this would equate to $62.1 million and $382.3 million in damages avoided, respectively. Clearly, the two models produce substantially different results. This would be expected given differences in the number and type of model variables and methodologies. It is also the main reason that benefit transfer studies, where results from one location are used to estimate ecosystem service values in another location, are problematic in their use. However, they do underscore the significance of the benefits provided by Turneffe Atoll's coral reefs, mangrove forests and seagrass beds.

The main constraint with bio-economic models, such as InVEST, often fall on the amount and quality of data available to meet model requirements. In the case of Belize, the government has scant resources to inventory mangrove forests, seagrass beds and coral reefs. Much of the data for the Belize InVEST model was funded by non-governmental organizations and academic research projects in addition to government-generated data (CZMAI 2016). Some of the data needed for the model, such as coral reef geometry (e.g., Burke 1982) is dated, some is incomplete (e.g., mangrove forest inventories), other data are inferred from data derived outside Belize (e.g., seagrass and mangrove physical parameters), or absent altogether (e.g., storm surge). By working with partners, Belize has assembled enough data to develop a useful model. Further research to update existing data to replace missing or inferred data will strengthen the InVEST model and the understanding of the role Turneffe Atoll's and the country's coral reefs, mangrove forests and seagrass beds play in protecting coastal resources and development.

The Belize InVEST model appears to perform well as their Conservation, Informed Management and Development management scenarios produced results consistent with expectations (CZMAI 2016). That is, under the Development scenario land protected from storms declined because of resultant mangrove and seagrass loss. Interestingly, the Informed Management scenario, which balanced development and conservation, produced the most benefits (damages avoided) while protecting nearly as much land as the Conservation scenario. Additional useful information could be generated by modeling incremental reductions in seagrasses or mangroves on Turneffe Atoll for their effects on land protected and damages avoided. Likewise, the benefits of mangrove and seagrass restoration could also be assessed for their ability to further reduce storm impacts in the future.

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