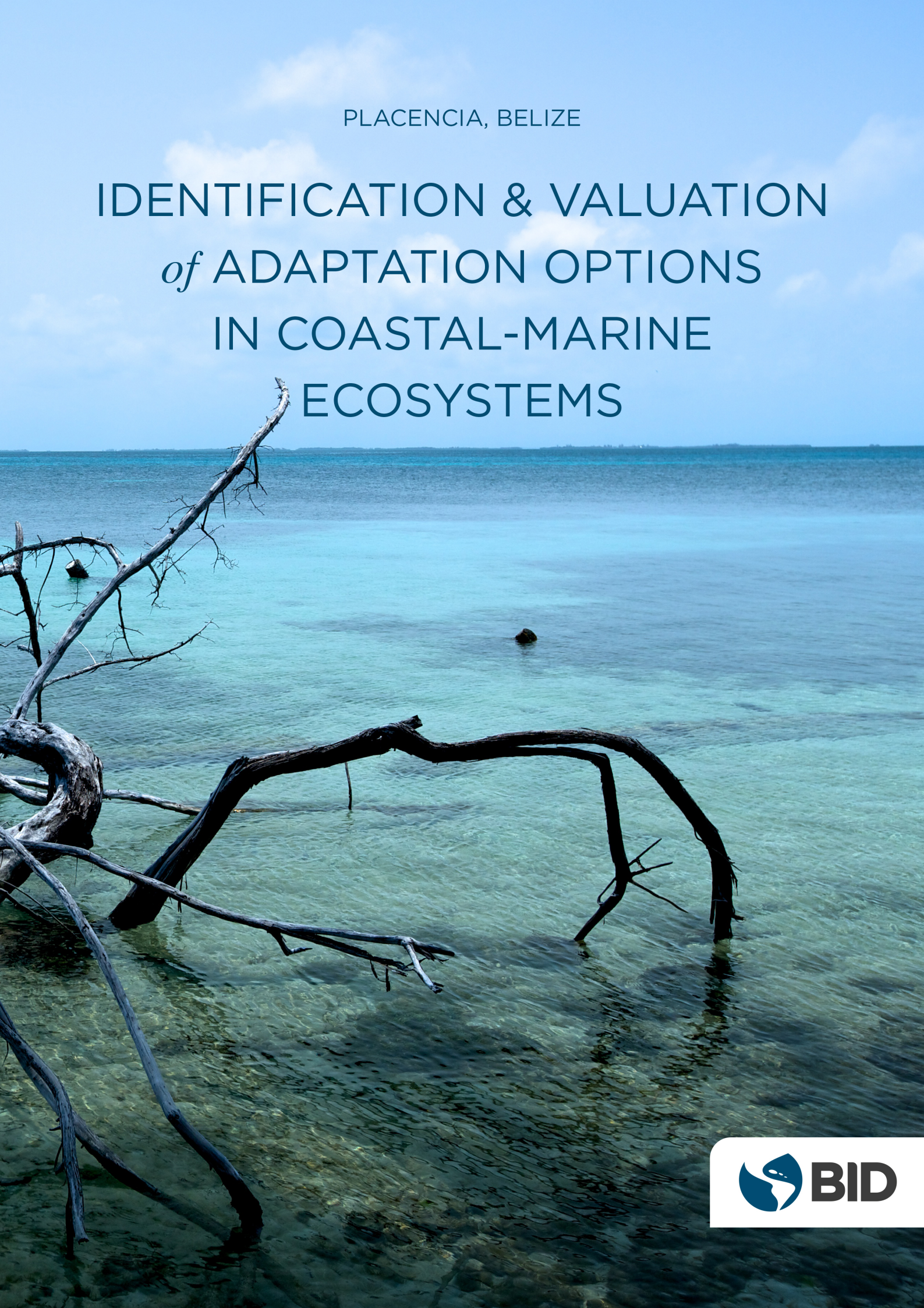
PLACENCIA, BELIZE

IDENTIFICATION & VALUATION *of* ADAPTATION OPTIONS IN COASTAL-MARINE ECOSYSTEMS



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Introduction

Climate change is expected to have serious implications on human health and welfare over the medium and long term. IPCC has already warned policy and decision makers on its 2014 Assessment Report (AR5) that crossing the 2C global average temperature threshold will create irreversible and unprecedented damage on local ecosystems in many regions, affecting communities and their livelihoods. Of particular concern are coastal regions, where sea levels are predicted to rise and ocean water to become warmer and more acidic- affecting herewith the composition of sea life, which is the basis of nutrition and recreation for coastal communities.

It is estimated that the costs related to physical impacts of climate change in Latin-America are in the order of US$100 billion per year- a number still very conservative to many experts. Various studies have indicated (Vergara et al, 2013; IPCC, 2014; Stern, 2006; Adger et al, 2005) that adaptation costs are however a small fraction of these estimated costs posed by climate change impacts and that they will increase with time. Thus, the sooner these adaptation actions are implemented, the greater the economic and social benefits obtained from them. However, it is important to mention, that in many cases the cost of these adaptation actions is very small compared to the benefits they generate to the society but in others they might not be as cost efficient. Therefore, the implementation of adaptation actions should be preceded by an economic analysis that can orient the prioritization process. Reaching fair estimations of these benefits and costs have been the corner stone of various studies found in the literature (Shardul, 2008; Howden et al, 2007; Weitzman, 2009 among others). In spite of their limited scope, these studies have significantly contributed new methods, tools and approaches to the field of climate change economics.

Of particular interest are ecosystems and their services, frequently taken for granted, and which climate change could put at imminent danger. Numerous studies on the costs of the economic impacts of climate change on different ecosystems have been generated in the past few years - these have been however very limited. In particular, existing analyses often face data and information constraints when aiming to capture the potential impacts of climate change to ecosystem services. One of the fields where additional work is still required is the assessment of the effectiveness of adaptation actions and how these can help maintaining or even improving the services these ecosystems provide to society. This study aims to address this gap by using ongoing work to characterize ecosystem services of coastal-marine ecosystems in Belize and assess potential impacts of climate change over these. Main goal is to use the outcomes of this process in the selection of adaptation options- followed by a cost-benefit analysis. Computational tools have been employed to better quantify climate change impacts and consequently assess identified adaptation options. In this regard, the Natural Capital Project's modeling tool, Integrated Valuation of Ecosystem Services and Tradeoffs (InVEST), is well suited to do this, since it combines spatial biophysical models with economic approaches to value market and non-market services, providing useful estimates with limited time and resources, and allowing the assessment of a full suite of services important to people who depend on coastal and marine environments.

The present study titled "Selected Economic Studies on Climate Change" has been financed through an Economic and Sector Work proposal (ESW). It contributes through a group of examples, closing identified data and informational gaps on adaptation actions to preserving services provided by key coastal ecosystems such as coral reefs, mangrove forests and seagrass beds. Specifically, the study makes use of an innovative, science-based methodology to assess adaptation options in coastal-marine ecosystems, taking as a pilot the region of Placentia in Belize. The study is divided in four sections, namely: (i) characterizing ecosystem services, (ii) designing climate change scenarios, (iii) designing climate adaptation scenarios and (iv) analyzing costs and benefits. It draws on pertinent literature including extensive work on ecosystem services carried out by WWF to date in Belize and introduces the methodological approach used by InVEST. The analysis has been concentrated on four key ecosystem services for Placentia, namely: (i) lobster catch and revenue, (ii) carbon & sequestration, (iii) tourism and recreation and (iv) coastal protection. .The document also addresses the most common approaches for assessing the costs and benefits of identified adaptation options, including their respective advantages and disadvantages, and provides a recommendation for the approach to be used.

It is important to note that this study is not intended to be comprehensive,, in this regard it is considered as a first step in a larger needed effort to better understand the extent of climate change impacts on coastal ecosystems and their services and to valuate adaptation options. In spite of its limitations, hopefully the study will contribute to the field of climate adaptation by showcasing an innovative approach to the assessment of costs and benefits of adaptation options on ecosystems and the services they provide to coastal communities. Initial results stemming from the analysis carried out in the study have significant potential for supporting policy-makers in making decisions related to coasts management and offer valuable lessons learned for next phases.

Overall Approach

We determined that the guiding question to be addressed by this study would be: *What are the relative costs and benefits of selected adaptation options in the Placencia region in Belize?* The approach to be piloted in this study aims to address some of the key constraints faced by cost-benefit analyses of adaptation options so far, and in so doing, strengthen the methodology for climate change adaptation planning.

In light of these considerations, the overall approach has included the following steps: (a) characterize ecosystem services in coastal-marine area of interest, (b) examine how the area might change as a result of development and climate change, (c) with key stakeholders, identify a subset of adaptation options, (d) quantify their respective costs and benefits based on valuation methods, and (e) conduct a spatial analysis of impacts on ecosystem services and resulting economic impacts. Each of these steps is explained in further detail below; steps (d) and (e) are combined.

First, a significant challenge of cost-benefit analysis is placing a monetary value on benefits – particularly ecosystem services. This analysis clearly demonstrates an **ecosystem service valuation methodology**, which quantifies and monetizes values for four key Caribbean ecosystem services adversely affected by climate change: the spiny lobster fishery, coastal protection, tourism/recreation, and carbon storage and sequestration.[1]

Second, this study makes clear the **spatial elements of climate risks and adaptation benefits**. Most climate adaptation assessments consider only the economic costs and benefits and ignore their spatial distribution across a landscape or seascape. Without this spatial information, it is not clear whether the places, habitats, and people put at risk by climate changes are also the beneficiaries of the risk mitigation of alternative adaptation measures. By applying InVEST, this study is able to provide maps of the risks and costs of climate change across the study area, which can be compared to the places that receive the most benefits from alternative adaptation options. This provides a new level of precision – and a first screen of equity and distributional effects – that are missing from most cost-benefit analyses.

Last, as recommended by the UN Secretariat for Climate Change (UNFCCC, 2011), this study draws on **strong stakeholder engagement** and **local capacity-building** for future assessments of climate adaptation options. Building on long-term relationships with the Belizean government and local decision makers, we solicited early feedback on proposed methods, variables, and processes. In addition, as an integral part of the study, we provided hands-on training for spatio-economic modeling of ecosystem service benefits and scenario development – two critical ingredients for cutting-edge analysis of adaptation options. These methods allow knowledge transfer in two directions – from scientists and economists to decision makers and vice versa – while increasing local adaptive capacity. They are also expected to produce higher-quality study results and foster their uptake by decision makers.

Consultation and Stakeholder Engagement

Stakeholders were consulted at each step; key stakeholders were engaged in the design of this effort to help design the approach at the outset. Since consultation was critical to this work and braided throughout each step, there is no individual section dedicated to stakeholder engagement. Instead, stakeholders, their input, and resulting decisions are included within each section. Stakeholders included representatives from civil society (such as WWF Belize, The Nature Conservancy Belize, Healthy Reefs Initiative, and the Toledo Development Corporation), Belizean government (Coastal Zone Management Authority and Institute, the Tourism Ministry and the Fisheries Department), academia (University of the West Indies and University of Belize), and representatives from Caribbean nations (Jamaica, Belize, Barbados, and Guatemala). The scope of this study did not allow for extensive engagement of local communities in Placencia Peninsula; however, we regard this as a valuable follow-up activity that should be considered to improve and disseminate initial results. At a workshop on coastal zone planning and climate adaptation held in Belize City in October 2012, we

[1] These services were initially identified as critical for Belize by the Coastal Zone Management Authority and Institute for the design of Belize's first Integrated Coastal Zone Management Plan (ICZMP)

presented our approach and gathered feedback from participants on each and every decision point – including climate variables, adaptation strategy, ecosystem services, costs and benefits – from stakeholders. This feedback was instrumental to the project and guided the methodological design and collection of data, which are outlined below.

A Note on Spatial Analysis

This study provides spatial information about the risks of climate change impacts and the potential benefits and costs of alternative adaptation options. In order to incorporate available data at appropriate scales and resolutions, the study was conducted at three levels: **national scale development** of climate scenarios, **local establishment** of adaptation measures integrated into a regional plan for the South Central Region, also known as Placencia Peninsula, and **regional analysis** of ecosystem service returns for Placencia Peninsula. The communities of Placencia Peninsula include Placencia Village, Seine Bight Village, and the Riversdale and Maya Beach neighborhoods (Fig. 1).

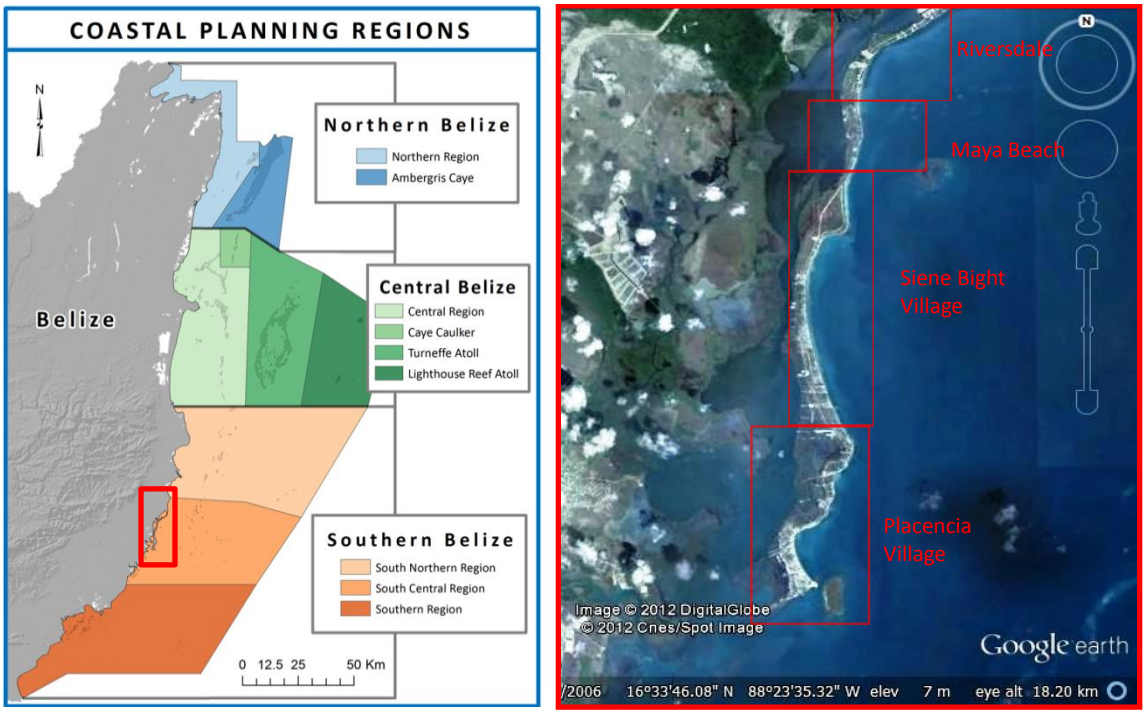


Figure 1. Nine coastal planning regions in Belize. This study focused on the South Central Planning region (medium shade of orange). In red is the zoom in on the right showing the Placencia Peninsula and villages.

Step 1: Characterizing Ecosystem Services

The most common definition of ecosystem services comes from the United Nations Millennium Ecosystem Assessment (MA): "the benefits people obtain from ecosystems" (Millennium Ecosystem Assessment, 2005). Ecosystem services are also referred to as environmental goods and services and nature's benefits. The services flow from the functions and processes of ecosystems, including the species that make them up (Daily, 1997). The MA (2005, 57) identifies four categories of ecosystem services:

1. Provisioning services that deliver goods such as food, water, timber, and fiber
2. Regulating services that stabilize climate, moderate risk of flooding and disease, and protect or enhance water quality
3. Cultural services that offer recreational, aesthetic, educational, and spiritual experiences
4. Supporting services that underpin the other services, such as photosynthesis and nutrient cycling

Alternative definitions and classifications have been proposed for specific contexts, such as landscape management, environmental accounting, and policy development (Boyd and Banzhaf, 2005; De Groot, Wilson, and Roelof, 2002; Fisher, Turner, and Morling, 2009; Wallace, 2007). In 2010, an international initiative, The Economics of Ecosystems and Biodiversity (TEEB), led by the United Nations Environment Programme (UNEP), proposed a definition that differentiates between the services provided by ecosystems and the benefits that humans receive from them (Kumar, 2010, 19). The TEEB classification for ecosystem services redefines supporting services as ecosystem processes, and includes a new category of habitat services, which provide nurseries for hunted or fished species and preserve future options by protecting genetic diversity.

Ecosystem Service Valuation

Economic valuation of ecosystem services involves assigning a monetary value to nature's benefits. Existing market prices often do not reflect ecosystem service values, and special valuation methods based on similar or hypothetical market situations are required. A 2004 white paper published by the World Bank clarifies the aims and uses of economic valuation of ecosystem services, outlining four principle objectives: assessing the value of the total flow of benefits from ecosystems, determining the net benefit of an intervention that alters ecosystem conditions, determining how the costs and benefits of ecosystem conservation are distributed, and identifying beneficiaries to ascertain potential funding sources for conservation (Pagiola, von Ritter, and Bishop, 2004).

The analytical approach for economic valuation of ecosystem services must be shaped to meet the specific objective. The framework often used to value these services is Total Economic Value (TEV), which includes the value of direct and indirect use of nature by people, values that are independent of human uses, and option value, or the benefits of preserving an ecosystem for future use. Yet, in practice there are seven principal methods used for ecosystem service valuation. These are:

- Market price approach, which estimates economic surplus based on a change in the quality or quantity of an ecosystem service which is exchanged in a formal market;
- Avoided cost approach, which estimates costs incurred in the absence of the service;
- Replacement cost approach, which estimates the cost of replacing the service with a man-made system;
- Production function or factor income, which estimates the contribution of the service to goods or income generation;
- Travel cost method, which estimates economic values associated with ecosystems or sites that are used for recreation. Assumes that the value of a site is reflected in how much people are willing to pay to travel to visit the site.
- Hedonic pricing, or the amount users demonstrate they are willing to pay for the service based on analysis of pricing and prior purchases; and

- Contingent valuation or choice modeling, or the amount service users indicate they would be willing to pay to obtain a service or the preferred option service users indicate, often through focus groups, surveys, or economic games.

Since the value of nature is not easily characterized—or fully captured—in monetary terms, many studies quantify ecosystem services values in terms of impacts on human health and nutrition, livelihood benefits, and cultural significance. Others simply measure ecosystem services in biophysical, rather than monetary, terms, such as tons of carbon sequestered. In this study, we will use economic valuation to incorporate ecosystem services into considerations of the costs and benefits of adaptation options.

Ecosystem Service Modeling: Methods and Use of InVEST

InVEST is a family of modeling tools that map, measure and value the goods and services we get from nature. InVEST enables decision-makers to assess the tradeoffs associated with alternative policy options, and to identify areas where investment in ecosystem services can enhance human development and conservation of terrestrial, freshwater, and marine ecosystems.

The biophysical steps in the models are based on equations and parameters in the primary literature for describing key processes in terrestrial, freshwater, and marine systems that are the basis for delivery of services. Similarly, InVEST uses well-established economic approaches, such as flood damage functions and return on investment measures, to value individual services and assess tradeoffs and synergies among multiple benefits to address specific decision contexts. InVEST models are spatially explicit. They take both spatial and non-spatial inputs and produce maps and summary metrics that can be used for information and communication purposes. The recently published book, Natural Capital: Theory and Practice of Mapping Ecosystem Services (Kareiva et al., 2011), describes the equations and theory that underpin InVEST. Appendix 1 to this document also lays out in greater detail how each of the models to be used in this study works, as well as each model's data sources, validation, limitations and assumptions.

Governments, companies, non-profits, and multilateral development institutions that manage natural resources can use InVEST to make better decisions. Since InVEST assesses multiple services and compares future scenarios, it is an effective tool for evaluating tradeoffs among uses and assessing the ecological, economic, and social impacts of alternative decisions. So far, InVEST has helped inform policy and program designs, such as land use and marine spatial plans, strategic environmental assessments, payment for ecosystem services, climate adaptation strategies, and mitigation and offsets.

InVEST is most effectively used within a decision-making process that starts with decision-makers identifying different management options. Decision-makers and researchers develop future scenarios to show, for example, alternative areas where marine protected areas might be established, where agricultural land might be converted to residential development, or where climate change is expected to affect precipitation and temperature patterns and therefore ecosystem health and function.

Combining these future scenarios with basic biophysical and economic input data, InVEST can estimate how the current distribution and value of relevant services are likely to change under alternative futures. The spatial resolution of analyses is defined by the user's interests and the quality of the input data; users can address questions at the local, regional or global scales.

InVEST applies multiple valuation methods, pairing each model with a method that produces measurable, useful outputs for decision makers. The primary methods include:

Market Value	Avoided Damage Costs	Production Function
Tourism	Water purification	Water for irrigation
Timber	Flood mitigation	Crop pollination
Non-timber forest products	Coastal protection	
Fisheries	Avoided reservoir sedimentation	Market or Social Value
		Carbon storage and sequestration

Ecosystem Service Modeling for This Study

In this study, we focus on several ecosystem services selected by Belizean government decision makers for their relevance to the region's economic stability and growth: coastal protection, spiny lobster fisheries, marine tourism and recreation, and carbon storage and sequestration. These services were initially identified as critical for Belize by the Coastal Zone Management Authority and Institute for the design of Belize's first Integrated Coastal Zone Management Plan (ICZMP). Since these services directly rely on the network of habitats in the coastal zone, a habitat risk assessment (HRA) tool can be used to identify locations where habitats are at the highest risk to degradation from human activities, and thus least likely to continue to provide the four ecosystem services we modeled (see Appendix 1 for further details on the outputs from the HRA tool and the following service models).

- **Coastal Protection:** To quantify the erosion protection value of habitats, the coastal protection model estimates the change in property damages from erosion due to the presence of habitat. This 'avoided damages' approach is the state of the art for assessing management options in places where storms threaten coastal properties.
- **Spiny Lobster Fishery:** To quantify the effect of habitat on increasing the productivity of fisheries, the fisheries model assesses differences in harvest due to a change in fish habitat, and then quantifies the value of that habitat using market costs and prices of expected harvest.
- **Tourism and Recreation:** The model estimates visitation based on different habitat scenarios and couples these results with information on common recreation expenses to quantify the value of habitat in driving tourism and recreation.
- **Carbon storage and sequestration:** The carbon model combines estimates of the social cost of carbon (USIWG 2010) with information about the distribution and abundance of coastal vegetation and habitat-specific carbon stock data and accumulation rates to estimate storage, sequestration and value across a landscape. The social cost of carbon is an estimate of the monetized damages associated with an incremental increase in carbon such as net agricultural productivity and human health.

Ocean and Coastal Services:	Valuation:
Coastal protection	NPV of avoided storm & erosion damages
Lobster fishery	NPV of harvested biomass
Marine tourism & recreation	NPV of tourism & recreation expenditures
Carbon storage & sequestration	NPV of carbon stored and sequestered

These process-based models are easily replicable for different scenarios and are designed to be adaptable to local data availability. The principal alternative method for quantified valuation of non-market goods like habitats relies on the use of surveys, which are time consuming, expensive, and of limited use in answering questions that lie beyond the scope of the survey.

The Implications of Ecosystem Service Analyses for Belizean Decision Makers

Through our work with the Coastal Zone Management Authority and Institute (CZMAI) we have used the InVEST models to quantify and value ecosystem services now and under future planning scenarios. The maps below illustrate the results for three ecosystem services under current conditions (year 2010). The first map shows the 2010 catch of spiny lobster for each of the nine planning regions (Fig. 2). InVEST lobster fisheries models estimate 0.52 million lbs of lobster tail are caught in the current scenario (2010) annually and that this yields BZ$16.4 million. These modeled results align well with observed data reported by the fisheries department of 0.61 million lbs of tail caught in 2011 and total revenue of BZ$16.85 million. The government of Belize is currently using these results to assess the spatial distribution of catch and revenue by planning region, and to reduce pressure on the fishery, and the coastal ecosystems that support it, by zoning

conflicting uses (e.g., marine transportation and coastal development) elsewhere to reduce the pressure on the mangroves and corals that provide habitat for lobsters and support the fishery.

The second map depicts the areas of the Belizean coastline where our model forecasts greatest erosion to occur as a result of storms and hurricanes (Fig. 2). Coastal habitats, such as mangroves, seagrass and coral reefs that provide protection for people and property, are a key component of the model (see Appendix 1). Using outputs from the model and information about the distribution and abundance of seagrass, mangroves and coral, the Belizean government has identified locations suitable for development or conservation and where conservation of coastal ecosystems is most crucial for reducing damages to people and property.

Lastly, outputs from the tourism and recreation model depict the distribution of tourism activity across the country in terms of the numbers of days that the different grid cells are visited by tourists. The Belizean government is using these results, coupled with maps of coastal habitats to show that of the three habitats, coral reefs tend to draw the most international tourists, locals use seagrasses for swimming areas and mangroves tend not to draw visitors. By identifying the habitats and locations, the government can identify where it is most critical to reduce risk to the habitats that support tourism.

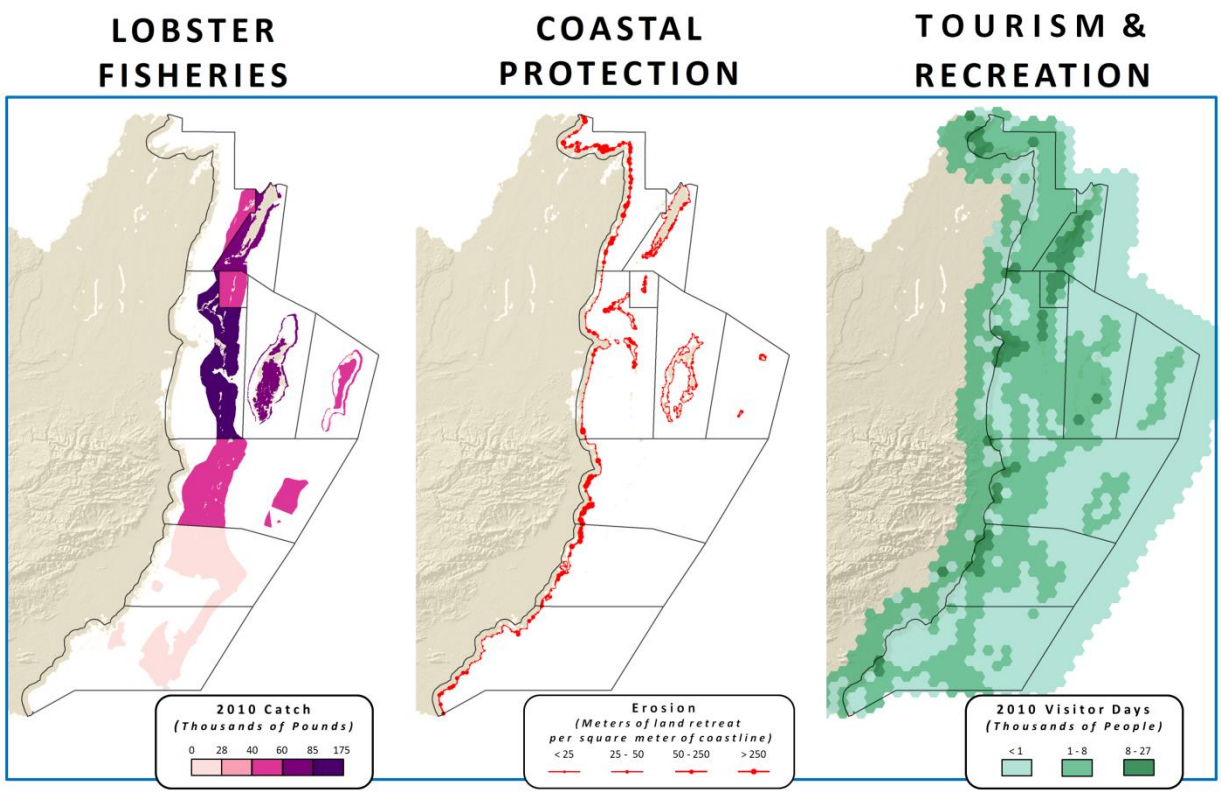


Figure 2. Annual results for the catch of spiny lobster, land lost to erosion and visitation rates along the coast of Belize for 2010.

Step 2: Designing Climate Change Scenarios

With the input of stakeholders in Belize and throughout the Caribbean, we identified four key stakeholders directly related to the ecosystem services being modeled in this study: (1) government decision makers, (2) the tourism industry, (3) the spiny lobster fishing industry, and (4) coastal property owners. All climate impacts and adaptation measures we address, and their associated costs and benefits, are targeted to the decisions and consequences for these four stakeholders.

Climate factors can influence ecosystem services both directly and indirectly through effects on coastal habitats (mangroves, corals, seagrass; see Figure 2). We have selected two focal climate variables for our climate change scenarios, based on (1) data availability and resolution, (2) a body of scientific literature and field research that clearly indicates likely impacts, and (3) relevance to the challenges and policies that Caribbean decision makers are considering. The two variables are: ocean temperature and sea level rise (Table 1).

Table 1: Two Climate Change Scenarios for 2100 and Supporting Literature

	Moderate	Intense	Literature/Approach
Sea level rise	0.5 m	2 m	Simpson et al 2010, IPCC 4th Assessment, Parris et al., in press
Ocean temperatures	+1.5 degrees C	+3.0 degrees C	IPCC 4th Assessment, Working Group II, Table 13.7, Simpson et al., 2010

Based on IPCC projections and stakeholder input at the Belize City workshop, we developed two climate change scenarios around these variables: Global Mitigation (moderate emissions) and Global Inaction (intense emissions) (see Snapshot). The Global Mitigation scenario represents the lower end of the projections for ocean temperatures and sea level rise for 2100. The Global Inaction scenario represents the upper end of the projections for the two variables (Table 1) for 2100. These scenarios are intended to bind the potential for climate change impacts on ecosystem services and people in Belize.

Snapshot | Global Mitigation vs. Global Inaction

Global Mitigation
In this scenario, the world takes mitigating actions to reduce greenhouse gas emissions through the UNFCCC, starting in 2020, as currently foreseen in international climate negotiations[2]. These mitigating actions slow climate change, resulting in 0.5m sea level rise and 1.5˚C increase in annual average temperature by 2100 in the Caribbean. As a result, consistent numbers of tourists seek to visit Belize year in and year out.

Global Inaction
In this scenario, the world fails to take strong mitigating actions to reduce greenhouse gas emissions within the timeline foreseen by the UNFCCC negotiations. As a result, global temperatures continue to rise and increase in their rate of rise, which continues to drive glacial melt at an alarming rate. In Belize, there are dramatic implications: by 2100, the sea level has risen by 2m and annual average temperature has increased by 3˚C, and is expected to continue. This affects the number of international tourists that visit Belize.

Available climate data tend to be global or regional in scale, very little is intra-national, and most of the time the data are not easily accessible or freely available. As a result of the limited information on spatial variation in projected increases in ocean temperatures and sea level rise for Belize, we applied a single set of parameters for the climate scenarios to the entire coast of the country (Table 1) and parameterized our ecosystem service models country-wide. Using the best available data (at a local scale where it was available or at a national or regional scale where it was not), we applied the Global Mitigation and Global Inaction scenarios for 2100 at the national level for Belize. In contrast, we applied detailed, policy-relevant adaptation strategies to the specific area of interest: the South Central Region surrounding Placencia (see Step 3: Designing Adaptation Scenarios below).

[2] We assumed global mitigation of GHG emissions began in 2020 as this is the end of the second commitment period (1 January 2013 to 31 December 2020) for Annex 1 parties to the Kyoto protocol . We did not specify the actual reduction in emissions because there is uncertainty around how reductions will translate into actual physical changes.

Climate Change Impacts on Ecosystem Services

Using these national climate change scenarios, we hypothesized how Global Mitigation and Global Inaction might affect our ecosystem services of interest. Based on existing literature and stakeholder review, we were able to establish likely relationships between ocean temperature and sea level rise and key parameters for ecosystem service provision (Fig. 3).

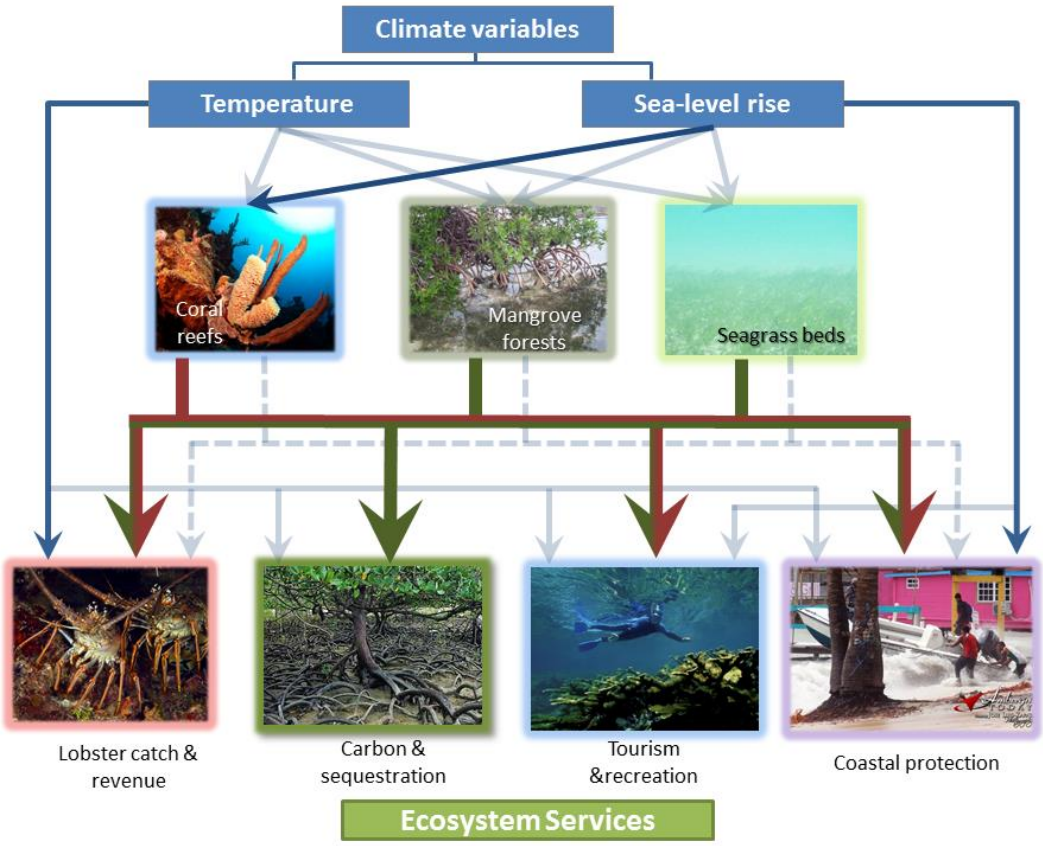


Figure 3. Potential effects of increasing ocean temperatures and sea-level rise on coastal ecosystems and the services they provide. Dark blue, green, and red lines are the relationships we included in this analysis. Transparent lines were not included (e.g., the direct effects of sea-level rise on seagrass and subsequent indirect effects of sea-level rise on tourism and recreation through impacts on seagrass), either due to model functionality, evidence in the literature or data availability. Solid blue, green, and red lines indicate direct effects of climate variables, coral and mangroves and seagrass respectively, and dashed transparent indicate indirect effects of climate variables via on services via their effects on the coastal ecosystems that provide services. Dark green (mangroves & seagrass) and red (corals) lines represent the role of habitats in delivering services. Solid blue lines are direct effects of climate on services (e.g., temp effects on lobster life history).

Using existing literature and data from local field studies, we were able to translate some of these hypotheses into quantitative relationships and data layers for use in the InVEST ecosystem service models. In other cases, there were insufficient data or understanding of the nature of the relationships between the climate change variable and ecosystem service to model robustly (see Gaps section). As a result, we were able to model climate impacts on two of our four service models: lobster fishery and coastal protection (see Table 2 and Figure 3). For these two services, the magnitude and direction of change were clear enough to model. Sea-level rise is likely to increase the impact of waves and storm surge on coastal areas through an increase in total height of waves and storm surge, thereby reducing the ability of coastal habitats to attenuate wave energy (Dean and Dalrymple, 1991; Tallis et al., 2011). Increasing ocean temperatures may reduce the expected survivorship of post-larval and juvenile spiny lobsters (Lourenco et al., 2008; Ehrhardt, 2005; Lellis and Russell, 1990; Witham, 1973), potentially leading to a reduction in population numbers and thereby resulting in lower catch rates for fishermen. Table 2 provides a description of the direct and indirect impacts of parameters and input data for each InVEST model that were adjusted to reflect differences in ocean temperature and sea level

rise between the Global Mitigation and Global Inaction scenarios. Those impacts in grey were not included in the final model runs. (See Appendix 1 for further details on InVEST model formulation).

Table 2: Climate and Ecosystem Impacts Affecting Ecosystem Services of Interest

Factor of Influence	Lobster fishery	Protection from storms provided by habitats	Tourism	Carbon storage & sequestration
Increasing ocean temperatures	Lower survivorship of post-larval and juvenile life stages, reducing lobster catch and revenue (Lourenco et al., 2008; Ehrhardt, 2005; Lellis and Russell, 1990; Witham, 1973)	The possibility of stronger storm intensity and frequency (IPCC, 2007; Hemer et al, 2013) could increase damages and decrease coastal protection services.		Decline in carbon sequestered in mangrove sediments due to increased decay rates. May be compensated by increase in productivity (Chmura et al, 2003).
Sea level rise		Rise in total water level of waves and storm surge, increasing coastal erosion and damages (Dean and Dalrymple, 1991; Tallis et al., 2011)	Reduction in land area for tourism development, decreasing visitation rates (results from Belize CZM planning process)	Decline in carbon storage in mangrove systems unable to maintain elevation at pace with SLR (McLeod et al., 2011)
Changes in coral cover and distribution, resulting from increasing ocean temperatures	Reduced adult lobster habitat and lower survivorship, reducing lobster catch and revenue	Reduced wave and surge attenuation, increasing coastal erosion and damages (Tallis et al., 2011; Lowe et al., 2005; Frihy et al., 2004)	Reduced tourism visitation rates and expenditures (Uyarra et al., 2005; results from BZ CZM planning process)	
Changes in mangrove distribution and abundance, resulting from sea level rise	Reduced postlarval and juvenile habitat and lower survivorship, reducing lobster catch and revenue (Acosta and Butler, 1997)	Reduced wave and surge attenuation, increasing coastal erosion and damages (Tallis et al., 2011; Quartel et al., 2007; Mazda et al., 2006; Mazda et al., 1997)	Reduced tourism visitation rates and expenditures (results from BZ CZM planning process)	Lower annual carbon storage and sequestration and corresponding value (McLeod et al. 2011)

Gaps: Climate Impacts on Ecosystems, Services, and Well-being

Given the current state of knowledge and predictions related to climate change impacts, as well as the complexity of these issues, there were unavoidable gaps in this study. We highlight these gaps to encourage further development of climate change science and modeling, and field studies that could increase our understanding of climate impacts on ecosystems and ecosystem services. We also identify areas where the information exists to fill these gaps given more time and resources devoted to incorporating the functionality to model climate scenarios into our ecosystem service models.

The direct impacts of climate change on carbon storage and sequestration and tourism were omitted from this study due to the complexity of these relationships and a lack of data at the level needed to adequately

model these changes. The ability of mangroves and seagrass to store carbon with increasing temperature is determined by the balance between increasing productivity and thermal stress that leads to changes in metabolism and growth. One of the key questions is whether increased productivity can compensate for increasing sediment respiration and this is not known for coastal wetlands (McLeod et al., 2011). The influence of sea-level rise on mangroves ability to sequester carbon depends on their ability to maintain elevation above the sea surface, which in turn is determined by sediment availability and root growth rates (Langley *et al.* 2009). These factors vary geographically and data at this level are not available in Belize. Likewise, modeling the direct impacts of climate variables on tourism were beyond the scope of this analysis because of lack of readily available information and justification for how climate change alters change in the number of tourists. A number of studies have shown that tourists climate preferences are neither constant over time nor across different countries (Besancenot 1990; Lise and Tol 2002; Morgan et al. 2000) and research on tourism climate preferences and other potential climate impacts on tourism has not been carried out for Belize. This is an area of study ripe for future work, and should be a priority, as our analysis below shows that tourism revenue plays a significant role in determining the outcome of our cost-benefit analysis of alternative adaptation options.

In the course of this work, we attempted to incorporate the indirect effects of ocean temperature increase and sea level rise on all four services via changes in coral reef and mangrove distribution and abundance. Climate change will likely reduce the total area of coral reef (and potentially mangroves), and will affect the health and function of these ecosystems (Hoegh-Guldberg et al., 2010; Doney et al., 2012, see Fig. 3, Table 2). However, the effects of climate on these ecosystems will vary considerably in space due to a variation in a suite of physical conditions that influence their distribution and abundance. There is an absence of published temporal and spatial projections for these habitats in Belize under future climate scenarios, and a lack of data and information needed to readily model the potential impacts of climate on mangroves, corals and seagrass.[3]

Another constraint was the limited time and capacity available for this study (4 months), which limited our ability to model sea level rise impacts on coastline retreat at a fine scale. To more precisely model changes in mangrove distribution and land loss, much finer resolution bathymetry data would be necessary. The resolution of existing bathymetry data for Belize is quite poor, as it is for much of the region and the limited timeframe of this work precluded the pre-processing of bathymetry data.

Finally, due to a lack of socioeconomic and demographic data and forecasting for Belize, we were unable to model how changes in ecosystem services might affect different demographic groups in the Placencia region. As a result, we provide spatial results about changes in ecosystem services from climate change and development factors, but we do not identify particular groups that would be most vulnerable to these changes or differentially quantify these impacts.

[3] We did model the effect of climate change on mangroves and coral reefs, but after consideration and internal peer review of the results, we excluded them from the study for lack of confidence in the outputs. For mangroves we applied the best available model for the effects of sea level rise on wetlands and coastal forests (SLAMM). This model has been developed and applied in the Gulf Coast of the United States (Geselbracht et al., 2011). Because this model was developed in areas with greater data availability it requires higher resolution bathymetry data than is currently available for Belize. Within the limited time of this study we were not able to revise the model nor ground-truth the results with local expert knowledge, which would have been important given the coarse input data. For corals we estimated change in distribution and cover based on local field studies of recent impacts of bleaching events and patterns in the literature on the general effects of temperature on these systems (Searle et al., 2012; Wilkinson and Souter, 2008). We excluded the coral reef projections under the two climate scenarios because we felt they were too preliminary to include in this study. Coral response to warming is highly variable and depends on a number of factors. We were only able to account for spatial variation in two of these factors: coral depth and flushing from freshwater inputs. Although these are two likely "rules of thumb" we did not have time to vet the results with local experts.

Step 3: Designing Climate Adaptation Scenarios

As an initial assay to evaluate adaptation strategies based on outcomes for ecosystem service provisioning, we selected a set of four climate adaptation scenarios to test during this consultancy.

Selecting Adaptation Strategies

To select the most appropriate four climate adaptation strategies, we drew on existing research with stakeholders in Belize that identified the 'best options' for sustainable development, adaptation, and mitigation of climate change in Belize (Bood and Fish, 2012; Bood, 2012). The goal of the existing research was to describe the theoretical linkages between climate change adaptation, mitigation and sustainable development in the coastal zone in order to develop a method to assess the extent of climate change 'triple wins' in reality. 'Triple wins' is becoming a commonly used term to refer to policies, programs, or projects that deliver benefits in the form of: climate change adaptation, mitigation and development, i.e., they should reduce emissions, enable people to adapt to climate change, and enhance local livelihoods and support biodiversity conservation. The study used key stakeholder interviews and focus group discussions with community members from Placencia and Seine Bight villages and representatives from the tourism development sector to prioritize. The adaptation options that were prioritized by this existing research (Bood and Fish, 2012; Bood, 2012) were selected based on the degree to which the communities and stakeholders felt that the practices were contributing to the aforementioned[4] (see Appendix 2a for participant list).

We combined those findings with an additional review of the literature to obtain proposed adaptation measures that particularly address the target audiences we identified. During the Belize City workshop with key stakeholders, we further expanded our list through brainstorming sessions with Belizeans and input from experts throughout the Caribbean (see Appendix 2b for full list of workshop participants). We prioritized measures that were (a) feasible for Placencia to undertake, (b) possible to map and value, and (c) clearly responsive to the impacts of climate change in the region, and thus relevant to other Caribbean nations. The list of possible adaptation options included:

POSSIBLE ADAPTATION OPTIONS:

- Mangrove and littoral forest conservation and restoration
- Private mangrove concessions
- Marine Protected Area (MPA) establishment
- Set-back for coastal development
- Sea wall construction
- Quotas for spiny lobster catch
- Decrease minimum catch size[5]

After the Belize City workshop, we examined the list of possible adaptation options and selected realistic adaptation strategies for the region. Selection criteria included: (1) stakeholders are actually considering the strategy in Belize, and (2) the strategy has the potential to influence one or more services we can currently model with limited if any advancement to our existing model formulations. As a result, the following adaptation measures were selected to be included in the adaptation scenarios:

1. Mangrove and littoral forest conservation and restoration
2. Marine Protected Area (MPA) establishment
3. Sea wall construction

[4] E.g. conservation/preservation of mangroves could contribute to (i) carbon sink (mitigation), (ii) coastal protection from storm and flood buffering (adaptation), and (iii) fish nursery function (development benefit).

[5] Expanded permitted catch size could temporarily maintain catch and revenue but in the long-term lead to dramatic decreases in stock and subsequent overfishing. This possible outcome is testable with InVEST models.

Scenario Storylines

As a result of discussions with participants at the workshop and with the Belizean government, we determined that comprehensive adaptation strategies – combining multiple discrete adaptation measures, as described above – are more valuable and realistic to assess than individual actions or measures. The decisions being made in Placencia, and throughout the Caribbean, concern a range of adaptation measures at different spatial and temporal scales, which must be adequately captured to analyze the costs and benefits. As a result, climate adaptation scenarios include one of the climate futures (described above) and a comprehensive adaptation strategy. In one alternative, the adaptation strategy involves a greater emphasis on conserving coastal vegetation (e.g. mangroves) and a lesser emphasis on gray infrastructure (seawalls). The second adaptation scenario puts a greater emphasis on gray infrastructure with less early action and green infrastructure. These adaptation strategies were reviewed by our partners in the Belizean government to ensure plausibility and relevance to policy decisions. Population increases, policies, and adaptation options are informed suppositions based on existing policies and decisions; no local forecasts exist for these scenario elements.

SCENARIO #1 – GLOBAL MITIGATION AND BELIZEAN INTEGRATED ADAPTATION

In this scenario, the world takes mitigating actions to reduce climate change impacts through the UNFCCC, starting in 2020, as currently foreseen in international climate negotiations. These mitigating actions slow climate change, resulting in 0.5m sea level rise and 1.5˚C increase in annual average temperature by 2100. As a result, consistent numbers of tourists seek to visit Belize year in and year out. After implementation of its Coastal Zone Management Plan, Belize takes early climate adaptation actions to safeguard its coastal resources and industries, with particular emphasis in important areas for tourism – a critical economic sector – such as Placencia Peninsula. Through a consultative process, the government of Belize fosters an integrated adaptation plan that combines green infrastructure strategies, such as conservation and restoration of coral reefs and mangroves that have the potential to adapt to climate change and are capable of providing protection from storms and sea level rise, with strategic use of gray infrastructure (i.e., building of sea walls in strategic locations). This is enacted through a combination of government interventions and incentives for the private sector and property owners. In Placencia Peninsula, we assumed the population increases from 1800 today to 2800 in 2100 based on conversations with local experts and their perception of population trends. Quantitative projects on population change were beyond the scope of this study. Note that the population estimates are not parameters in any of the analyses so these numbers are purely for descriptive purposes.

Snapshot | Adaptation Scenario #1	
Timeframe	2100
Climate impacts	0.5m sea level rise, 1.5˚C temperature increase
Adaptation strategy (green)	Protection of coastal mangroves and littoral forest Some restoration of mangroves Establishment of MPAs Strategic construction of sea walls to avoid undeveloped and conservation areas and beaches that are used for tourism; model outputs for seawall heights were 0.25 to 2.75 m
Placencia population	2800
Level of development	Low to moderate

SCENARIO #2 – GLOBAL INACTION AND BELIZEAN INTEGRATED ADAPTATION

In this scenario, the world fails to take mitigating actions to reduce climate change impacts within the timeline foreseen by the UNFCCC negotiations. As a result, global temperatures continue to rise and increase in their rate of rise, which continues to drive glacial melt at an alarming rate. In Belize, there are dramatic implications: by 2100, the seal level has risen by 2m and annual average temperature has increased by 3˚C, and is expected to continue. This affects the number of international tourists that visit Belize. However, after implementation of its Coastal Zone Management Plan, Belize takes early climate adaptation actions to safeguard its coastal resources and industries, with particular emphasis in important areas for tourism – a critical economic sector –

such as Placencia Peninsula. Through a consultative process, the government of Belize fosters an integrated adaptation plan that combines green infrastructure with strategic use of gray infrastructure, including protection of mangroves and littoral forests and some building of sea walls in strategic locations. This is enacted through a combination of government interventions and incentives for the private sector and property owners. In Placencia Peninsula, we assumed the population increases from 1800 today to 2800 in 2100 based on conversations with local experts and their perception of population trends. Quantitative projects on population change were beyond the scope of this study. Note that the population estimates are not parameters in any of the analyses so these numbers are purely for descriptive purposes.

Snapshot | Adaptation Scenario #2	
Timeframe	2100
Climate impacts	2m sea level rise, 3˚C temperature increase
Adaptation strategy (green)	Protection of coastal mangroves and littoral forest Some restoration of mangroves Establishment of MPAs Strategic construction of sea walls to avoid undeveloped and conservation areas and beaches that are used for tourism; model outputs for seawall heights were 3 to 6 m
Placencia population	2800
Level of development	Low to moderate

SCENARIO #3 – GLOBAL MITIGATION AND BELIZEAN REACTIVE ADAPTATION

In this scenario, the world takes mitigating actions to reduce climate change impacts through the UNFCCC, starting in 2020, as currently foreseen in international climate negotiations. These mitigating actions slow climate change, resulting in 0.5m sea level rise and 1.5˚C increase in annual average temperature by 2100. As a result, consistent numbers of tourists seek to visit Belize year in and year out. After the implementation of the Coastal Zone Management Plan, however, Belize takes few early actions for climate adaptation. Actions are taken only as new areas along the coast are developed and more urban areas appear. Where coastal development is high, gray infrastructure is the primary emphasis, and sea walls are built by the government to protect investments in tourism and private property. With only a minor focus on green infrastructure, some areas of mangrove and littoral forest are protected while others will be lost, and no areas are restored. In Placencia Peninsula, we assumed the population increases from 1800 today to 3500 in 2100, with an influx in ex-patriots drawn to 'sun and beach' marketing by Belize. We based these population increases on conversations with local experts and their perception of population trends. Quantitative projects on population change were beyond the scope of this study. Note that the population estimates are not parameters in any of the analyses so these numbers are purely for descriptive purposes.

Snapshot | Adaptation Scenario #3	
Timeframe	2100
Climate impacts	0.5m sea level rise, 1.5˚C temperature increase
Adaptation strategy (grey)	Construction of sea walls along all coastlines with development; model outputs for seawall heights were 0.25 to 2.75 m Some protection of mangroves and littoral forest
Placencia population	3500
Level of development	High

SCENARIO #4 – GLOBAL INACTION AND BELIZEAN REACTIVE ADAPTATION

In this scenario, the world fails to take mitigating actions to reduce climate change impacts within the timeline foreseen by the UNFCCC negotiations. As a result, global temperatures continue to rise and increase in their rate of rise, which continues to drive glacial melt at an alarming rate. In Belize, there are dramatic implications: by 2100, the sea level has risen by 2m and annual average temperature has increased by 3˚C, and is expected to continue. This affects the number of international tourists that visit Belize. After the implementation of the

Coastal Zone Management Plan, Belize takes few early actions for climate adaptation. Actions are taken only as new areas along the coast are developed and more urban areas appear. Where coastal development is high, gray infrastructure is the primary emphasis, and, sea walls are built by the government to protect investments in tourism and private property. With only a minor focus on green infrastructure, some areas of mangrove and littoral forest are protected while others will be lost, and no areas are restored. In Placencia Peninsula, we assumed the population increases from 1800 today to 3500 in 2100, with an influx in ex-patriots drawn to 'sun and beach' marketing by Belize. We based these population increases on conversations with local experts and their perception of population trends. Quantitative projects on population change were beyond the scope of this study. Note that the population estimates are not parameters in any of the analyses so these numbers are purely for descriptive purposes.

Snapshot | Adaptation Scenario #4	
Timeframe	2100
Climate impacts	2m sea level rise, 3˚C temperature increase
Adaptation strategy (grey)	Construction of sea walls along all coastlines with development; model outputs for seawall heights were 3 to 6 m Some protection of mangroves and littoral forest
Placencia population	3500
Level of development	High

In addition to the four scenarios described above, we also designed a No Action scenario in which the configuration of coastal and marine uses (e.g., coastal development and conservation areas) remains the same as in the current scenario. We crossed this No Action future with the Global Mitigation and Global Inaction scenarios to produce a total of one current and six future climate change and adaptation scenarios.

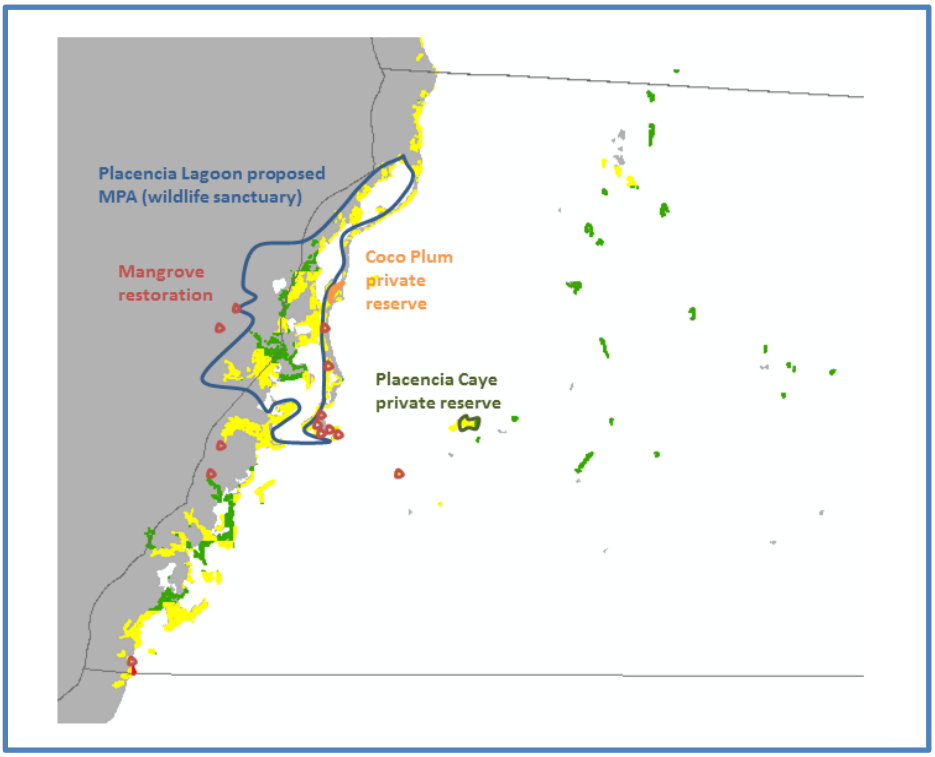


Figure 4. Proposed green strategies for the Integrated Adaptation scenario include an MPA (blue), fourteen mangrove restoration sites (red), and two private reserves (orange and dark green). Output from the Habitat Risk Assessment model from the Belize government coastal zone planning process is shown for mangroves in yellow (medium risk) and green (low risk). Note that the HRA output is for risk to habitats based on human activities, not climate (see Gaps Section). We assumed that medium risk sites within the locations where green strategies are proposed would be low risk in the future, as these strategies would reduce the impact of human activities on mangroves.

Spatial Design of Adaptation Scenarios

Once we selected the three adaptation strategies (i.e.,MPAs, mangroves and littoral forest conservation and restoration, and seawall construction), we combined local stakeholder knowledge and information from the literature to convert the scenario storylines and adaptation strategies into three spatial-temporal scenarios for implementing the climate adaptation strategies (i.e., Integrated, Reactive and No Action see below). Crossing these three adaptation scenarios with our two climate change scenarios results in six total scenarios in our analysis (see Figs 8 and 9 and Table 7a &b) This process involved deciding the spatial extent, placement, and magnitude of the various strategies, and how to reflect the different strategies in terms of parameters and input data layers into the models.

The study area encompasses the South Central region of Belize. This area includes two villages (Placencia and Seine Bight) and two neighborhoods (Maya Beach and Riversdale). On the southwest margin of the Placencia Lagoon lies a third community, Independence Village. It is an area renowned for its tourism and under current pressure for further tourism development (Fig. 1). In addition to widespread and biologically important mangroves, littoral forest, and coral reefs, the Placencia Lagoon is also an important ecological feature. Placencia Peninsula is located near a number of marine and terrestrial protected areas, a status which allows for some of the surrounding natural environment to be safeguarded and protected in order to maintain the integrity of ecosystems. Nearby marine protected areas include Gladden Spit and Silk Cayes, South Water Cayes, Sapodilla Cayes, Glover's Reef Marine Reserve, Laughing Bird Caye National Park and Port Honduras. Terrestrial reserves that are adjacent to Placencia include Cockscomb Basin Wildlife Sanctuary and Deep River Forest Reserve, among others.

Integrated Adaptation scenarios #1 and #2 emphasize green approaches to climate adaptation, such as restoration and conservation of mangrove and littoral forests to protect the shoreline for residents and tourists, and to sustain livelihoods through fishing for lobster (Fig. 4). These scenarios also include some seawalls for shoreline protection (Fig. 5). The Integrated Adaptation scenario builds on a coastal zoning scenario that came out of our work with the Belize National government and blends strong conservation goals with current and future needs for coastal development and marine uses. It assumes that conservation would be implemented in areas that are currently protected, undeveloped, or proposed for conservation status in the Belize Integrated Coastal Zone Management Plan. We assigned areas for implementation of restoration for climate adaptation in areas where restoration activities are already underway and areas proposed for restoration (Fig. 4). Some restoration sites exist along the southern end of the peninsula and the southwestern section (Placencia Village) and others are on the Cocoplum Resort property (Seine Bight Village). Proposed restoration sites include the entire southern tip of the Peninsula, and the southeastern and southwestern sections in certain areas where mangroves have been cleared over the past couple of years, but which are not being fully used for other activities. We assigned the gray approach to adaptation in the form of seawalls to areas that are currently highly developed or proposed for development in the Belize Integrated Coastal Zone Management plan. These are areas with low potential for mangrove restoration.



Figure 5. Coastal development and seawalls location for each of the three future scenarios.

We used a similar approach to assign implementation of seawalls, conservation and restoration of coastal ecosystems to specific locations in Reactive Adaptation scenarios #3 and #4, but emphasized gray over green strategies. Because the storyline for these scenarios suggests that coastal development increases dramatically in the Placencia region, we increased development throughout the region, according to a high development scenario created during our work with the Belize national government during the coastal zone management planning process (Fig. 5). This development scenario for the Integrated Coastal Zone Management process was created based on information from stakeholders about the areas already permitted for development and those areas most likely to be developed in the future. In these scenarios we assumed seawalls would be implemented for climate adaptation in all areas with infrastructure. We employed a design model for engineered structures (see Appendix for Coastal Protection Model) that determines the size of seawalls (i.e., height parameters) needed to prevent damages under the two different climate change scenarios. The cost-benefit analysis incorporates differences in implementation and maintenance costs for the two different sets of seawall design criteria. All undeveloped areas were left as they are without assuming any investment in conservation.

The No Action adaptation scenario mirrors the current configuration of marine and coastal uses of the environment, including coastal development, aquaculture, fishing, conservation and oil exploration, among others. Information for these uses was gathered as part of the coastal zone planning effort in Belize.

After identifying the spatial locations for implementing the green and gray strategies in each scenario, we determined how to use the models to analyze the effects of these strategies on services (Table 3). Area of mangrove forests is an important input variable into the lobster fishing, tourism and coastal protection models. Thus, the effect of changes in mangroves on these services through conservation, restoration and development in the four scenarios can be analyzed using the InVEST models. Other attributes of mangrove forests are important for coastal protection, such as the density and width of trunks, which could be influenced by the age of the forest. For simplification purposes, we assumed that both Integrated and Reactive approaches within the scenarios were implemented and completed in 2025, which is the end of the 15

year planning horizon for the Integrated Coastal Zone Management process currently underway. This means that the forests would be fully restored by 2025 and capable of providing services from 2025 to 2100 (see Cost Benefit Analysis and Economic Gaps sections below).

Table 3 identifies how the selected adaptation measures affect key ecosystem services and the resulting changes that are incorporated into each InVEST model (See Appendix 1 for further details on InVEST model formulation).

Table 3. Adaptation Measures and the Mechanisms Through which They Affect Key Ecosystem Services

Adaptation measure	Lobster fishery	Protection from storms	Tourism	Carbon storage and sequestration
Seawalls	Decrease in post-larval and juvenile habitat and survivorship	Increase in wave and surge attenuation and reduction in erosion and damages	Potential for both positive and negative effects. Seawalls and coastal development increase risk to corals but also provide infrastructure for tourism.	Increase in risk of mangrove and seagrass degradation from coastal development decrease carbon storage and sequestration
Marine Protected Areas (MPAs)	Increase post-larval, juvenile, adult habitat and survivorship	Increase wave and surge attenuation	Mangroves have limited influence on tourism. Corals have large influence on tourism.	Increase carbon storage and sequestration
Restoration and conservation of mangroves and littoral forests	Increase post-larval and juvenile habitat and survivorship	Increase wave and surge attenuation	Mangroves have limited influence on tourism	Increase carbon storage and sequestration

Step 4: Analyzing Costs and Benefits

As agreed, we compare among alternative adaptation options to identify costs and benefits of alternative approaches given a suite of ecosystem services addressed by case study. Costs will be incorporated directly into the scenarios and InVEST. Costs include the costs of adaptation implementation combined with any associated costs to ecosystem services quantified by our models, and benefits will be represented by the positive return in ecosystem service values quantified by our models. The particular costs and benefits will depend on the adaptation options selected and the data available.

Selecting an Assessment Methodology

There are several methods for assessing the costs and benefits of different options, and we aim to select the most appropriate method using the latest guidance from trusted sources, including peer-reviewed literature and the United Nations Climate Change Convention bodies. The UN Secretariat for Climate Change (2011) has identified three commonly used methods to assess the costs and benefits of adaptation and provided guidance on best practices for the use of those methods. These prioritized techniques are:

1. COST-BENEFIT ANALYSIS (CBA) – calculates and compares costs and benefits, expressed in monetary terms; helps determine efficiency of adaptation investments.

Benefits: CBA is the most comprehensive tool to estimate economic outcomes when allocating scarce resources. The benefits of CBA include the potential to compare multiple options and categories of costs and benefits across a single metric, monetary value. CBA results, whether expressed in net present value (NPV), benefit-cost ratio (BCR), or internal rate of return (IRR), allow users to easily prioritize among identified options. It provides clear information about the efficiency of alternative options, which is the aim of this study. In addition, CBA has been a primary tool used to evaluate the costs and benefits of adaptation options in particular economic sectors and coastal zones in assessing climate adaptation options, particularly for sea level rise and extreme events (UNFCCC, 2010).

Drawbacks: Despite these advantages, there are drawbacks to using CBA for climate adaptation. CBA is not designed to incorporate factors for equity and distributional effects. For analyses where subsistence income is a critical factor, CBA will need to be adjusted, e.g. to account for subsistence values. For example, a study in Namibia found that in the worst case climate scenarios, total GDP in Namibia would be lowered by 5%, but approximately half the population would have their livelihoods destroyed (Stage 2010). In cases where it is especially important to know the distribution of costs and benefits, CBA may not be sufficient to make societal decisions.

An additional drawback is the challenge of placing a monetary value on non-market values, such as health, ecosystem services, and aesthetic or cultural values. While there are techniques to apply non-monetary values, such as contingent valuation and hedonic pricing, these can be time-intensive and costly to assess (Klein and Tol, 1997). However, InVEST is particularly well suited to handle this challenge as it is designed to use market and non-market valuation to place a monetary value or a social value on ecosystem services. As a result, this study can push the boundaries of climate adaptation assessment by including a fuller set of costs and benefits related to ecosystem services.

Uncertainty: Uncertainty about included values is a key challenge in all of the methods identified. In CBA, it can be addressed by: (1) by factoring in a range of values for market and non-market benefits and (2) conducting analysis with multiple climate scenarios (UNFCCC, 2011).

2. COST-EFFECTIVENESS ANALYSIS (CEA) – identifies the least costly option for meeting pre-determined goals; does not perform a broader economic analysis to determine whether the identified measures are worthwhile, rather it examines the least-cost method to arrive at adaptation objective

Benefits: CEA is most appropriate when adaptation goals are clear and well-defined, and benefits are difficult to measure monetarily, such as human health, biodiversity, and cultural ecosystem services (UNFCCC 2011). Unlike CBA, CEA is most useful to express adaptation benefits that are difficult to monetize. CEA can be conducted relatively quickly, since it is a reduced form of CBA where only costs are measured in monetary form. It is effective at allocating limited resources among options to reach a pre-determined policy goal.

Drawbacks: The most critical drawback of CEA for this analysis is that it is not designed to compare multiple adaptation options or objectives, which is the mandate of CZMAI as it seeks to balance different objectives and stakeholder interests when defining zoning options. Each goal (e.g., health, tourism, lobster fishery) would require conducting a separate CEA, with an additional layer of analysis to standardize and compare results. It is also important to note that CEA does not assess the economic validity of the policy goal itself as benefits are not measured monetarily (Klein and Tol, 1997). In addition, all costs considered by the analysis need to be quantifiable, unlike MCA (see below).

Uncertainty: In CEA, uncertainty can be addressed by: (1) identifying win-win or low-regret projects, i.e. projects that would provide benefits in absence of climate change (Accounting for the Effects of Climate Change, 2009).

3. MULTI-CRITERIA ANALYSIS (MCA) – measures alternative adaptation options against a set of criteria with different assigned 'weights'; the highest resulting score is the best adaptation fit

Benefits: MCA is most useful when data are scarce or when the targeted benefits and costs are hard to quantify. In CBA and CEA, economic efficiency is the single decision making criterion, whereas in MCA, it can be one of many. In another advantage, not all criteria need to be expressed in monetary terms (Klein and Tol, 1997). In addition, criteria can be expressly included in an MCA to account for equity and distributional impacts, which are not well addressed in CBA and CEA. The multiple-criteria format also allows stakeholders to have a voice in creation of criteria, which can lead to more learning and uptake of the results.

MCA is becoming increasingly common over the last 30 years in cross-sector analyses to account for valued criteria that do not translate easily into monetary terms, such as health and ecosystem services (although InVEST can now help quantify and monetize these). National Adaptation Programs of Action (NAPAs) in particular favor MCAs, which include an explicit participatory process with stakeholders (UNFCCC, 2010).

Drawbacks: Despite MCA's popularity in cross-sector analyses, it is less common in sector-specific and small-scale assessments to spur adaptation (UNFCCC, 2010). MCA is most appropriate when information on monetary benefits of adaptation is lacking and informed judgment must be used in its stead. For example, MCA might include interviewing local communities to gain qualitative knowledge of how they have adapted to similar events in the past or anticipate they would adapt (World Bank, 2010). As a result, building uncertainty into account is a challenge (see below). It is difficult to determine the robustness of the analysis, and the weights assigned to criteria can be contentious.

MCA is the most resource and time intensive of the three options (UNFCCC, 2010). It can take months to years to complete a comprehensive MCA and requires the cooperation of a range of stakeholders and experts. In this study, it would add substantial time and resources relative to the other options, particularly since CBA would still likely be one of the primary criteria in the decision making process.

Uncertainty: In MCA, uncertainty can be addressed by: (1) including flexibility and resilience as one of the criteria in the analysis, thereby prioritizing salutations that allow for adjustment to changing social and climate scenarios, (2) making efficiency one of the criteria for analysis which would be measured through a CBA, and (3) conducting comprehensive data-gathering with stakeholders and experts to appropriately evaluate (and apply weights to) each criterion.

Recommendations for all methodologies

The UN Secretariat for Climate Change (2011) recommends several strategies to reduce uncertainty and increase relevance and legitimacy. These include:

- Consider multiple adaptation options
- Incorporate more than one climate scenario
- Involve stakeholders
- Conduct sensitivity analysis and select discount rates carefully
- Take into account distributional effects

For This Study

We apply a Cost-Benefit Analysis for this study, based on the strengths and weaknesses of the alternative methods. The results will help Belizean government decision makers compare among possible adaptation options in Placencia and along the coast. First, this approach most clearly assesses the costs and benefits of alternative adaptation options in an efficient way; it is also standard in many sectors and countries, and so can be easily understood and incorporated into decision-making. Second, standardizing both costs and benefits, such as ecosystem services, in monetary values will enable cross-sector decision-making and allow a more complete economic assessment of options. Although a drawback of typical CBA is the difficulty monetizing ecosystem services, the strength of the InVEST models is their ability to do just that under alternative scenarios, so this common drawback will be mitigated. Third, CBA allows appropriate inclusion of key stakeholder inputs and feedback from the Belize City workshop and local expert review to select ecosystem services and adaptation options, but is less time-consuming and resource-intensive than MCA, an important consideration in light of the timing and funding constraints of this study. Fourth, a goal of this study is to advance the science of selecting adaptation options, using a methodology that can be easily undertaken by decision makers and provide a clear indication of the option that will offer the best outcomes. CBA is the most efficient and replicable methodology to pursue given available time and resources.

Cost-Effectiveness Analysis is not an appropriate option because there are no specific, pre-determined policy goals for the study to draw on. Additionally, CEA is not well suited to comparing multiple goals and objectives; evaluating options for the spiny lobster fishery, coastal protection, and tourism/recreation would each require a separate CEA. Multi-Criteria Analysis is a less desirable option than CBA for two reasons: first, MCA is very resource and time-intensive, which is not easily replicable at a local level; and, for this study cost-effectiveness is the ultimate objective, so including additional criteria to respond to multiple objectives is less critical.



Source: Adapted from BOYD R AND HUNT A. 2004. *Costing the Impacts of Climate Change in the UK: Overview Guidelines.* UK Climate Impacts Programme Technical Report.

Figure 6. Decision tree for selecting among CBA, CEA, and MCA for a climate adaptation assessment, identifying the best methodological option for this study.

Following this study and contract period, it may be valuable to further this work by expanding the CBA into a full MCA, including a stakeholder review of the initial CBA results. Stakeholder input during the CBA phase of the evaluation may reveal that cost-effectiveness is not the only important criteria. With this guidance, and additional time and resources, it may be beneficial to add new, relevant criteria to the assessment and thereby integrate the CBA into a broader MCA. This may be particularly useful to address questions of equity and distribution of costs and benefits. The multi-criteria results have the potential to bolster the decision making process among options that have similar rates of cost-effectiveness.

After selecting the CBA approach, we identified the appropriate methodological approach to compare the costs and benefits of adaptation options based on our timeframe and resources. We selected the cost-benefit analysis (CBA) and outlined a basic set of equations to compare adaptation options over time. Because the benefits and costs of adaptation options under different climate change scenarios are both uncertain and spread over time, we calculated an net present value *NPV* using a discount rate, , of 5%[6] over the time horizon of the scenarios.

$$NPV_a = \sum_{t=0}^{T} \frac{B_t}{(1+r)^t} - \left(\sum_{t=0}^{T} \frac{I_t}{(1+r)^t} + \sum_{t=0}^{T} \frac{D_t}{(1+r)^t}\right) \qquad \text{Equation 1}$$

Where B_t, I_t, and $D_t$are the respective benefits, implementation costs and damages in year t of choosing adaptation measure a. To assess if an adaptation policy is efficient, we compared it to a no-action policy, i.e. $NPV_a - NPV_{NoAction}$.

[6] In the absence of information on the best discount rate to use for Belize, we chose the highest (5%) of the three discount rates available in the USIWG 2010 technical document (i.e., 2.5%, 3%, 5%). The social discount rate should be higher in less advanced economies because the political, social, and market stability of these countries tends to be lower than in more economically advanced countries. Thus, we assume that the general population of a country such as Belize would have a stronger time preference than that observed in a country such as the United States.

Climate Change and Adaptation Costs and Benefits

The costs and benefits are given generically in our basic cost-benefit equation (above), as we extend the reach of their meaning beyond simply accounting for direct climate-based changes in welfare to encompass other spillover effects from management decisions. For example, mangrove restoration may benefit property owners by reducing the harmful effects of coastal storms, but it also increases the habitat for fish and can yield larger harvests for coastal fishing communities. Similarly, seawalls may protect coastal property, but in addition to their construction cost they may also negatively influence coastal tourism. It is important to capture these effects in order to more fully characterize the tradeoffs between different policies.

We used our models to quantify the potential costs and benefits of climate change and alternative adaptation strategies to lobster fishing and coastal protection and alternative adaptation strategies alone to tourism and carbon storage and sequestration. Our ecosystem service models provide a useful framework for tackling a complex set of issues in the limited timeline of this consultancy. The level of detail we were able to produce directly relates to the parameters, input data, and current functionality of the models (see Appendix 1 and Tallis et al., 2011 for more details). Based on the existing, literature, stakeholder input and expert review, we identified outputs from the existing models that would be most relevant to Belizean decision-makers, the public and private sectors.

Expected biophysical and economic costs of sea level rise and increasing temperature (amount of change varies by climate scenario):

- Change in average annual catch and revenue of spiny lobster between now and 2100 (BZ$)
- Change in average annual damage to property (erosion) from storms between now and 2100 (BZ$). This output includes the role of natural ecosystems in providing protection from storms.

Based on the existing literature, stakeholder input and local expertise, we quantified the cost of implementing and maintaining the climate adaptation strategies we evaluated. In addition to costs of implementation and maintenance, we quantified potential unintended consequences of these strategies for lobster fishing, tourism, carbon storage and sequestration and damages to coastal property using our ecosystem service models and a model for estimating the height of seawalls needed to prevent coastal erosion.

EXPECTED COSTS OF ADAPTATION MEASURES:

- Seawall construction (BZ$) and potential costs to services of associated development (BZ$)
- MPA establishment and management and potential costs to services (BZ$)
- Mangrove & littoral forest planting and potential costs to services (BZ$)
- Opportunity cost of adaptation measures (these were limited to trade-offs between the services we modeled. For example, development of the coast for tourism in the Reactive scenario led to a decrease in mangrove habitat to support the lobster fishery).

Using our storylines, spatial scenarios for Integrated and Reactive adaptation approaches, three models for ecosystem services, model for seawall protection from storms, information from the literature, and stakeholder expertise, we quantified the benefits of adaptation options in terms of revenue from lobster and tourism, carbon storage and sequestration, and avoided damages to coastal infrastructure.

BENEFITS OF ADAPTATION MEASURES:

- Change in average annual tourism revenue between now and 2100 (BZ$)
- Change in average annual catch and revenue of spiny lobster between now and 2100 (BZ$)
- Change in average annual damage to property from storms between now and 2100 (BZ$). This includes change in the average annual value of natural protection from storms between now and 2100 ($BZ)
- Change in annual carbon storage, sequestration and value between now and 2100 (BZ$).

We used the annual values for ecosystem services, implementation and maintenance costs, and damages from coastal erosion) to calculate the Net Present Value (NPV) of each of these components for each of the six future climate change management scenarios (i.e., Global Mitigation and Global Inaction x No Action, Integrated, Reactive). We then contrasted Integrated Adaptation, which emphasizes green infrastructure, and Reactive Adaptation, that focuses on grey solutions, to the No Action adaptation scenario under both the Global Mitigation and Global Inaction scenarios.

Sourcing economic data

The economic data used in this analysis came from a variety of sources. The data used to value ecosystem services and quantify damages from storms and sea-level rise were gathered through an extensive three year stakeholder engagement process, search of the grey and peer-reviewed literature, and from government, non-governmental and academic sources in Belize.

- Spiny lobster catch and revenues are based on annual catch data provided by the Belizean Ministry of Forestry, Fisheries, and Sustainable Development (Fisheries Department).
- Tourism data are based on annual visitation to Belize recorded by the Belize Tourism Board and projected under the Sustainable Tourism Plan for Belize. Spatial data are based on a database of thousands of geo-tagged photos downloaded from the website Flickr.
- The social value for carbon was derived from estimates in a United States Interagency Working Group Report on Social Costs of Carbon published in 2010 and adapted to the Belize context (see Appendix for more information on social costs of carbon).
- Property values are derived from a narrow census of real estate in Placencia Peninsula and averaged across the region.

Implementation costs were gathered through our stakeholder and expert workshop, local industry and NGO contacts and from the scientific and grey literature. We give an overview here with details listed in the tables below.

- Annual MPA management costs come from estimates calculated by WWF Belize (Table 4).
- Mangrove and littoral forest planting costs were derived from existing restoration projects in Placencia on a per area basis (Table 5).
- Costs of private reserves include a $50 application fee to the Belize Association of Private Protected Areas (BAPPA) and $50 annual membership fee.
- Sea wall construction and management costs are estimated based on peer-reviewed literature and accessible private sector information from construction companies (Table 6).

Combining economic data (e.g., per lb value of lobster, construction costs for different heights of seawall) with the biophysical outputs from our models (e.g., lobster catch, required seawall height to avoid flooding) allows us to map ecosystem service returns, damages, and implementation costs. Accounting for spatial variation within, as well as among scenarios, is a more accurate approach for understanding how changes in the ecological and social systems affect the benefits that Belizean people rely upon from nature and the consequences of climate adaptation planning. In particular, understanding where things happen in space facilitates more integrated management actions that make use of both grey and green strategies and where these are best used individually and in combination.

Table 4. Implementation and maintenance costs for one MPA (approximately 5000 hectares)

Implementation (at start up)	Cost (US $)
Consultations, management plan development, zoning, Cabinet paper, equipment sourcing (e.g. boat)	60,000.00
sub-total Implementation	*60,000.00*
Maintenance (per year)	
Staff Salaries	
Biologist	12,500.00
Protected Area Manager	22,000.00
Rangers (2)	17,500.00
sub-total Salaries	*52,000.00*
Enforcement	
Infrastructure	17,000.00
Fuel	7,800.00
Food Allowance	3,900.00
Vessel Maintenance	6,780.00
General Supplies	1,200.00
Capacity Building	4,925.00
Insurance, License & Permits	650.00
Communication	2,000.00
sub-total Enforcement	*44,255.00*
Scientific Monitoring	
Water Quality	7,500.00
MBRS	550.00
Commercial Species	2,100.00
Turtles	675.00
Birds	1,575.00
Climate Change indicators	2,500.00
sub-total Monitoring	*14,900.00*
Overall Total	*171,155.00*

Sources: Nadia Bood estimated based on costs for nearby MPA (approximately 5000 hectares) at Laughing Bird Caye. MBRS stands for Mesoamerican Barrier Reef System. As it related to scientific monitoring, it is the monitoring protocol developed by the MBRS that is used by MPA for their biological monitoring.

Table 5. Implementation and maintenance costs for mangrove restoration (per 300 m2)

Implementation	Cost (US$)
Seedlings or transplant collection	3,000
Planting activity	12,000
sub total implementation	*15,000*
Maintenance (per year)	
Monitoring of growth/status	4,000
Replanting if needed	500
Community outreach	2,000
sub total maintenance	*6,500*
Overall Total	21,500

Sources: Nadia Bood

Table 6. Implementation and maintenance costs for piled seawall

Implementation (per m of seawall)	Cost (US $)
Construction	1,177.52
Additional costs per m height over 1 m	11.78
Maintenance (full rebuild every 25 years)	

Sources: Construction (pers. communication with Carla Maheia Hart, Managing Director Maheias United Concrete & Supplies Ltd., Belize City, Belize. Linham et al, 2010, page 54.

Results

Ecosystem services

We quantified the potential effects of climate adaptation strategies on four ecosystem services, carbon storage and sequestration, lobster fisheries, coastal protection and tourism, and the habitats that provide these services. In this section we do not report results for coastal protection because in our cost-benefit analysis these results are included in the damages calculation (see below). We were only able to model impacts of climate change on two of the four services – lobster fisheries and coastal protection. We modeled changes in services under one current and six future scenarios. The six future scenarios consist of two climate scenarios (Global Mitigation and Global Inaction) that represent different levels of climate change crossed with three management scenarios (No Action, Integrated and Reactive) that represent different adaptation strategies. The current scenario represent the time period 2010-2024. The future scenarios represent the time period 2025-2100. First we assessed differences in the risk to three habitats, seagrass, corals and mangroves, among the three future management scenarios using the InVEST Habitat Risk Assessment tool. Second, we combined outputs from this analysis with data reflecting the climate scenarios and fed these into the ecosystem service models.

Our habitat risk assessment results suggest that the Reactive Adaptation scenario will lead to the greatest area of mangroves, corals and seagrass at high risk of degradation from human activities (Fig. 7). Among these three habitats, we find the most area of coral reef at high risk, followed by the seagrass and mangroves. Coastal development and the associated building of seawalls is only part of this reason for high risk. The Reactive scenario is based on the coastal planning scenario that emphasizes not only coastal development, but also an increase in associated uses, such as transportation routes for cruise ships and water taxis that could impact corals and seagrass. The increase in area of mangroves at risk (relative to the No Action scenario) is primarily due to effects of coastal development and associated building of seawalls along much of the coast of the South Central Region (Fig. 7, and see Fig. 5 above depicting the location of coastal development and seawalls).

In contrast, our results suggest that the area of habitat at risk will tend to decrease with Integrated Adaptation relative to the No Action scenario, with area of mangrove at low risk increasing by almost a factor of 10. These results emerge not only from the restoration of mangroves, institution of private reserves, and MPAs, but also from a reduction in the cumulative impacts of multiple human uses of the coastal zone that is the result of the Belize government designing an informed coastal zoning scheme on which this Integrated Adaptation scenario was based.

In addition to differences between scenarios, the area of habitat at high, medium and low risk will vary spatially within the South Central Region. For example, the area of mangroves at medium risk increases in the Integrated scenario, relative to No Action, in the north due to new development for tourism, where, as the area of mangroves at risk decreases in the central part of the region around the lagoon and Placencia Peninsula because of the proposed MPA, private reserves and restoration areas. These differences in the risk of habitat degradation within the study region, as well as between scenarios, are critical for understanding where and to whom the services provided by mangroves, corals and seagrass are most likely to change in the future.

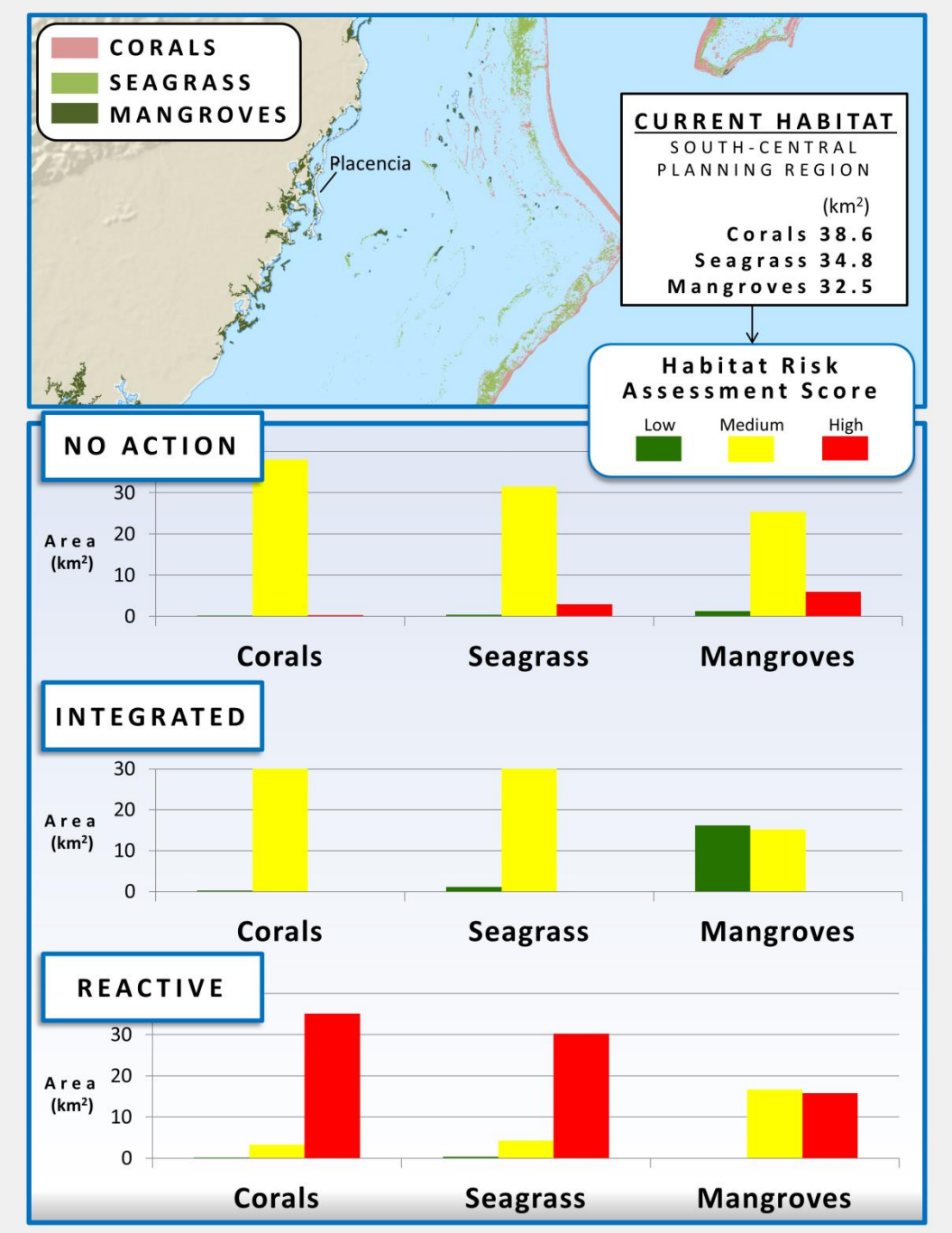


Figure 7. Risk of degradation to coral reef, mangrove forest and seagrass beds under three alternative adaptation scenarios: No Action, Integrated and Reactive.

We assessed the potential influence of climate change and adaptation strategies on lobster catch and revenue using the InVEST Lobster Fisheries model (see Appendix 1 for further details on this model). Our model estimates that the South Central Region currently contributes 70,000 lbs of catch and $750,000 gross revenue to the country (note that these figures are for tail and head weight and so are higher than the data in Fig. 2 which includes just tail weight). Outputs from the future scenarios suggest that the impact of warming temperatures may lead to large reductions in catch and revenue, regardless of which adaptation strategy is

implemented. Our models suggest that reductions in revenue with climate change may be moderately improved by implementing the Integrated Adaptation scenario instead of taking no action (i.e., BZ $205K versus BZ $250K under Global Inaction, Fig. 8). The catch and revenue under the Reactive scenario fares the worst, most likely due to degradation and loss of nursery (mangrove and seagrass) and adult (seagrass and coral) lobster habitat.

Unlike lobster, the potential impacts of climate on tourism and carbon storage and sequestration were less clear in the literature and more complicated to model given the short time frame of this study (see Gaps in climate scenarios). Thus we did not model the effects of climate change on these services, but instead modeled the consequences of the climate adaptation scenarios (designed to reduce damages and support lobster) for tourism expenditures and carbon storage, sequestration and values. We found that the Integrated Adaptation scenario is likely to result in over twice the number of days visitors spend in the South Central Planning region relative to the Reactive scenario and nearly 1.5 times the revenue. The Integrated scenario also performs considerably well compared to the No Action scenario. This is because the Integrated scenario blends conservation of key habitats that support tourism with some increases in development in the northern part of the planning region which will support tourism expansion. In addition, this scenario is based on a country-wide scenario that incorporates research conducted by the Belize Sustainable Tourism Board specifically designed to draw a greater number of tourists to the country.

Our findings for carbon storage and sequestration align with the general pattern we observed for other services. Carbon storage, sequestration and value provided by seagrass and mangroves is likely to be highest in the Integrated Scenario relative to the No Action and Reactive scenarios. Note that we quantified carbon storage, sequestration and value under the Integrated and Reactive scenarios *relative* to the No Action scenario, since for regulating services it is unrealistic to quantify the service through comparisons to bare ground. The increase in total carbon value[7] in the Integrated scenario occurs through restoring stock and also increased accumulation of carbon in sediments associated with that stock over time. Decreases in carbon value in the Reactive scenario occur from loss of mangrove and seagrass stock as a result of an increase in coastal development, construction of seawalls and associated activities (e.g., expanded marine transportation routes for cruise ships and water taxis).

[7] Note that the price per ton of carbon changes through time. The price changes because the damages from a net positive increase in atmospheric carbon in a given time period affects the state of the global economy *at that time* (and into the future from that point). Since the models underlying these prices project a changing economy, the prices are necessarily different across time periods because a larger economy incurs more damage from a given ton of emissions.

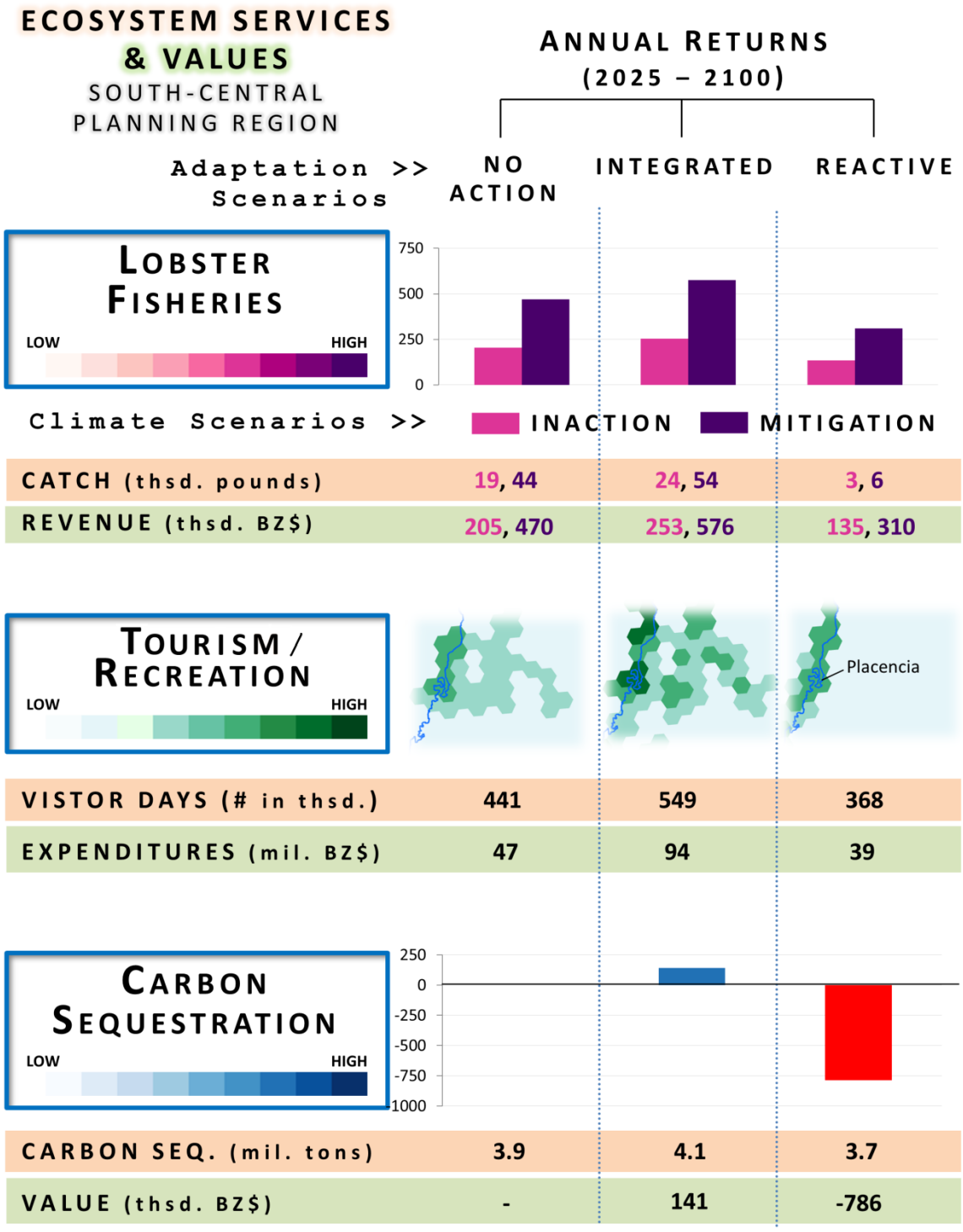


Figure 8. Annual returns of three ecosystem services, lobster, tourism and carbon, for the South Central Region of Belize under the three climate adaptation scenarios. Note that the lobster results are for catch and gross revenue from lobster tails and heads. Note that carbon storage and sequestration values for the Integrated and Reactive scenarios are relative to the No Action scenario.

Damages from storms and sea-level rise

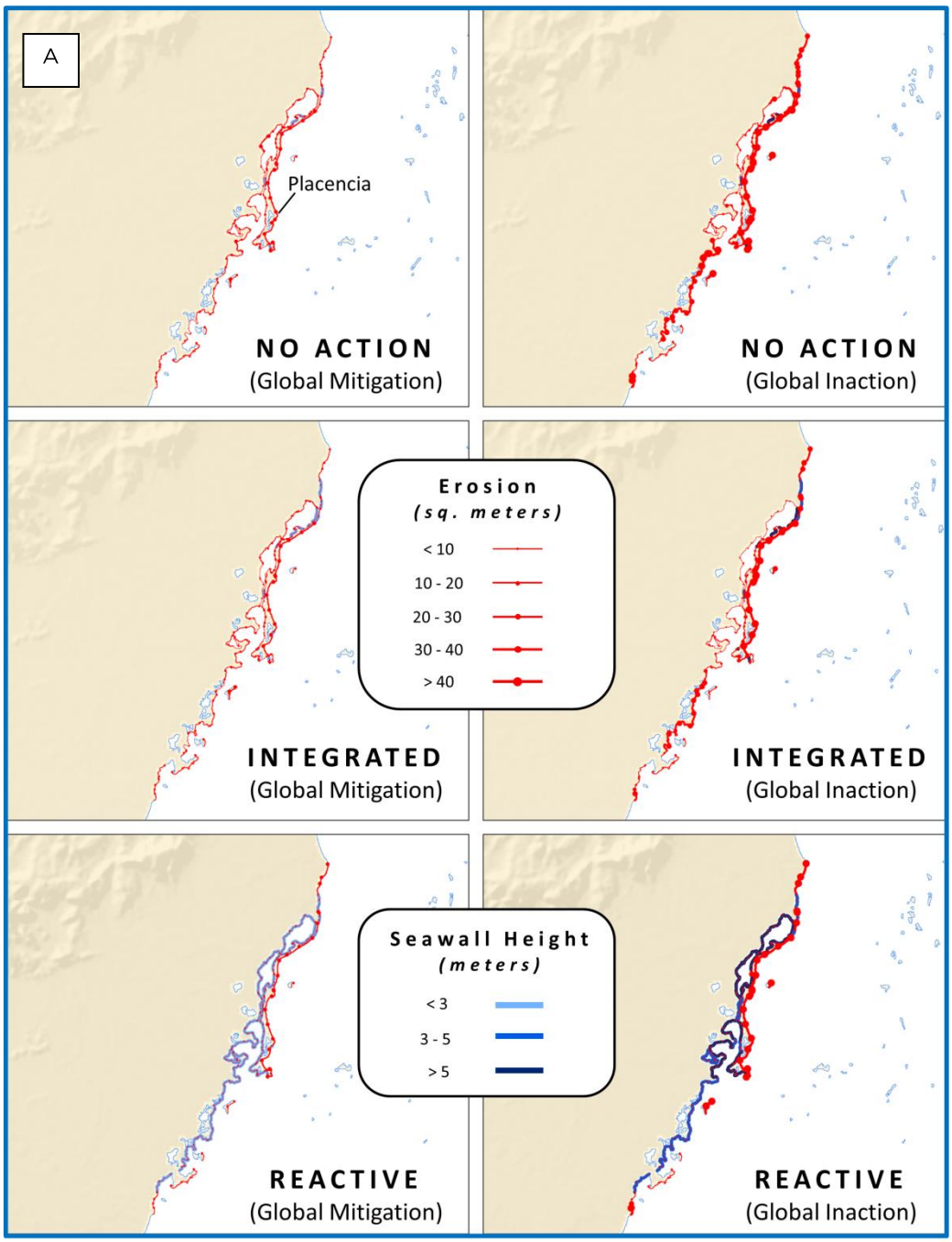
A primary concern about a future with climate change is the effect of warming temperatures and sea level rise on erosion and flooding from sea-level rise and storms. This project was largely about assessing the ability of coastal ecosystems to provide an alternative form of protection for people and property from coastal hazards. To do this, we first used our coastal protection model to assess differences in damages under the alternative climate and adaptation scenarios. The model incorporates the ability of mangroves, seagrasses and corals to attenuate waves and water levels during storms, reducing the amount of erosion, or lost land, as a result of the action of the ocean on coastal areas (see Appendix 1 for more detail). The model is particularly useful in this context because it produces outputs in both biophysical (distance of land retreat or erosion) and economic ($ value of lost land based on property value) metrics. The biophysical metrics are important for identifying where erosion is likely to be most problematic. The economic variables are important in the cost-benefit analysis.

We found that erosion varies considerably both within the study region and between scenarios. In general, our models predict the most erosion along the windward side of the Placencia Peninsula, likely because of its exposure to storm waves and surge (Fig. 9). In addition, note in Figure 9 that there are few if any seawalls (in blue) on the windward side of the Placencia Peninsula. This is because this region is very important for tourism, an industry that relies on pristine sandy beaches that would be lost with seawall construction. In addition, damages tend to be high here because of the high value development for tourism on the Peninsula.

Erosion also differs between scenarios, with our models predicting less erosion under the Integrated Adaptation than No Action scenario and the least erosion in the Reactive scenario. Reduced erosion in the Integrated relative to No Action scenario likely results from an increase in mangroves due to restoration and decrease in risk to corals and seagrasses as a result of better management of a suite of human uses. In some areas the results for these scenarios look similar because there were no differences in management actions – for example the ecosystems along the east coast of the Placencia Peninsula are similar in the No Action and Integrated scenario. In other areas, such as the west coast and southern part of the lagoon, the amount of erosion is two to three times lower in the Integrated scenario in which mangroves are restored for adaptation purposes.

That erosion is lowest in the Reactive scenario may at first seem counter-intuitive. This is because the Reactive scenario has the most coastline devoted to seawalls (Fig. 9 pictured in blue). We assume no erosion and no damages occur with seawalls present and instead use modeling approaches to design the seawalls based on the height needed to avoid damages (see following section and Appendix 1 for more information).

Lastly we find that erosion and damages from erosion are greatest under the Global Inaction scenario. This is due to two different factors. First, increased sea levels lead to an overall increase in the water level along the coast, which results in more erosion. Second, we accounted for the influence of sea level on the interaction between coral accumulation rates and water level relative to the reef crest. The depth of the reef crest is a very important parameter in the model for predicting wave attenuation by coral reefs. Rises in sea level lead to greater depth and weaken the ability of corals to provide protection from storms, unless they are able to keep up their height with accretion. We used published estimates of accretion rates and assumed where habitat risk was low from the impact of human activities, that corals were able to keep pace with sea level rise. Where risk was medium, corals provided some protection but it was limited based on the greater depth. Where risk was high, corals were too degraded to provide protection.


A
Placencia
NO ACTION
(Global Mitigation)
NO ACTION
(Global Inaction)
Erosion
(sq. meters)
< 10
10 - 20
20 - 30
30 - 40
> 40
INTEGRATED
(Global Mitigation)
INTEGRATED
(Global Inaction)
Seawall Height
(meters)
< 3
3 - 5
> 5
REACTIVE
(Global Mitigation)
REACTIVE
(Global Inaction)

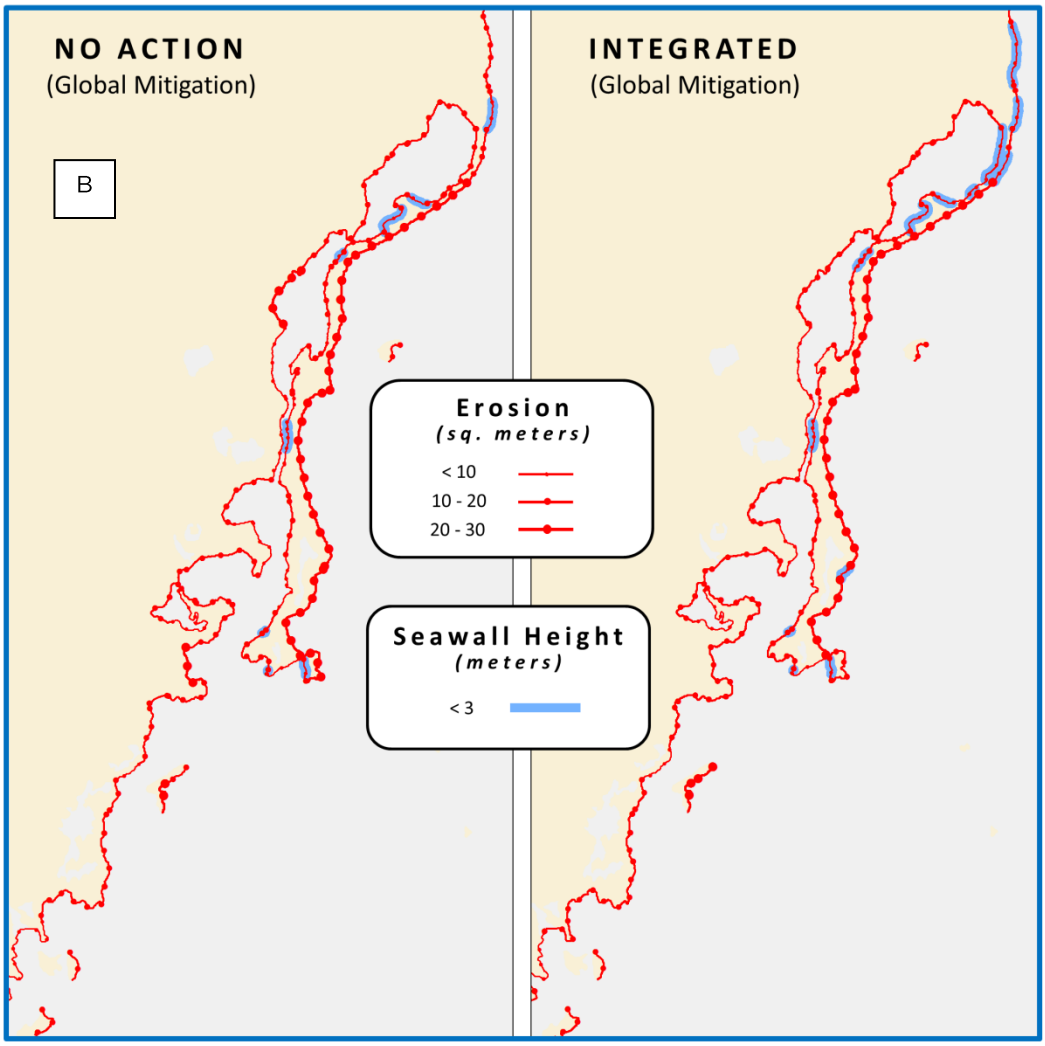


Figure 9. A) Erosion and engineered protection from a single category 1 hurricane event under three alternative management and two climate scenarios. B) Results for No Action and Integrated with Global Mitigation. Erosion (red) estimates were produced from the coastal protection model in all areas WITHOUT seawalls. A seawall overtopping model was used to estimate the height of seawalls (blue) needed to provide protection based on local conditions for regions WITH seawalls.

Seawall heights, implementation and maintenance costs

After quantifying current and future damages in areas without seawall using the coastal protection model that accounts for differences in the distribution, abundance and protective capacity of habitats between scenarios, we used a set of well-established coastal engineering equations to develop a model for estimating the seawall height required to prevent overtopping of flood waters during a storm event. We estimated required heights for those locations with seawalls in the current and future scenarios and quantified differences in the required heights under the different climate scenarios for sea level rise. We found that overall the Global Inaction scenario required higher seawall height than the Global Mitigation scenario and that the Reactive scenario included the greatest length of coastline protected with seawalls (Fig. 9).

We then combined our modeled estimates of seawall height and lengths of coastline protected by seawalls in each of the scenarios, with economic information from local engineering firms and grey literature (see Table 6) to estimate costs of constructing and maintaining seawalls along each section of coastline. By basing these estimates on our model outputs for each scenario we were able to take into account spatial variation in

exposure to coastal hazards (e.g., from coastline orientation etc.) and differences between climate scenarios. We then combined all the spatially explicit information into a single number for costs for seawalls (keeping implementation and annual maintenance costs separate because they are incurred in different years) for each future scenario and fed these into the equations for net present value (see Appendix 1 for more detail). Estimates of the net present value of implementation and maintenance of the grey strategies (seawall) within each scenario were then combined with the costs of the green strategies (see adaptation scenarios section above) and included in the cost-benefit analysis (see NPV tables below).

Discussion

The aim of this study was to examine the relative costs and benefits of different adaptation options under consideration in Belize. Our goal was to highlight the use of a valuation methodology that can be used to quantify and monetize values for key ecosystem services under different future scenarios and therefore inform decision-making processes. The work presented here represents a first attempt to incorporate climate change into the modeling of ecosystem services in Belize. We developed possible future climate scenarios and adaptation strategies that may be implemented to reduce vulnerability to the negative impacts of climate change and estimated their effects on services using InVEST, a tool that combines economic and biophysical models and data to quantify and map benefits from nature. The use of future scenarios is useful in planning given the uncertainty surrounding projections for climate variables and the impacts of these on ecosystems and the services that they provide. Here we examined both low and high emissions scenarios that bound a range of possible futures.

Our results show that the Integrated Adaptation approach, which emphasizes green adaptation options, such as MPA establishment and mangrove restoration, has the best overall return under both high and lower emissions climate scenarios (Table 7). Both management scenarios (Integrated Approach and Reactive) result in a decline in Net Present Value compared to the current situation but losses are lower than with no action. The Integrated Approach resulted in the lowest loss of coastal habitats (e.g., corals, mangroves and seagrass), which are critical for maintaining lobster fishing, coastal protection, carbon storage and sequestration and tourism. The Integrated Approach also results in an increase in benefits from carbon storage and sequestration, in contrast to the decrease under the Reactive approach. Note that these are *net* changes in atmospheric carbon, where the baseline is the no action case. We assume that any historical natural trends in carbon fluxes are the same across scenarios with the only differences between scenarios attributable to differences in the result of the adaptation strategies. Damages from erosion from sea-level rise and storms were highest for the Integrated Approach[8] but these are balanced by lower implementation costs and higher benefits. Similar patterns are seen under both Global Mitigation and Global Inaction emissions scenarios.

Table 7. Net Present Value of benefits, costs and damages for each of the adaptation scenarios

[8] The damages are higher for the Integrated Adaptation scenario over the Reactive scenario because of the assumption we make that developed land is more valuable than undeveloped land. Based on property value data for the region, the model values developed land more than undeveloped land to reflect people's values. This also means that the same area of erosion of developed land leads to greater damages in Belizean dollars than undeveloped land. This concept is very important for understanding and interpreting the results from the coastal protection model and the cost-benefit analysis. Our results suggest that overall erosion is generally less in the Integrated than No Action scenario, which results from conservation and restoration of habitats that shield coastal communities because the Integrated Adaptation scenario includes new development for tourism the overall value of the land is greater, leading to higher value property that is lost due to erosion.

a) Global Mitigation (billions)

		Adaptation Scenarios	
	No Action	Integrated	Reactive
NPV of total benefits	$0.790	$1.300	$0.650
NPV Lobster fishing	*$0.008*	*$0.009*	*$0.006*
NPV Tourism & recreation	*$0.782*	*$1.273*	*$0.702*
NPV Carbon storage & sequestration	-	*$0.013*	*-$0.061*
NPV of total implementation costs	-$0.005	-$0.015	-$0.191
NPV of erosion damages from sea level rise and storms	-$2.517	-$2.556	-$2.005
Total NPV of all benefits, costs and damages	-$1.731	-$1.275	-$1.550
NPV compared to No Action scenario	-	$0.456 billion	$0.181 billion

b) Global Inaction (billions)

		Adaptation Scenarios	
	No Action	Integrated	Reactive
NPV of total benefits	$0.789	$1.293	$0.647
NPV Lobster fishing	*$0.007*	*$0.007*	*$0.005*
NPV Tourism & recreation	*$0.782*	*$1.273*	*$0.702*
NPV Carbon storage & sequestration	-	*$0.013*	*-$0.061*
NPV of total implementation costs	-$0.005	-$0.021	-$0.339
NPV of erosion damages from sea level rise and storms	-$3.59	-$3.66	-$2.82
Total NPV of all benefits, costs and damages	-$2.803	-$2.392	-$2.515
NPV compared to No Action scenario	-	$0.411 billion	$0.288 billion

The Reactive adaptation approach had the highest implementation costs due to the high costs of building and maintaining seawalls. However, coastal damages were lowest under this scenario as we assumed, for simplification purposes, that seawalls provide complete protection to coastal lands behind them. Damages would have been even lower if seawalls had been included on the windward side of the peninsula. However, this approach was not considered to be realistic given that this area is intensively used for tourism and has a number of beaches that are used by tourists.

According to the results of this analysis, the Integrated Adaptation scenarios is more efficient when compared to the no-action scenario. However, the total NPV of all benefits, costs and damages is indeed negative for both the Integrated and Reactive scenarios. A negative NPV generally indicates a bad investment. However, because “no action” is the baseline for the actual decision context (essentially no investment) the investment in the Integrate and Reactive adaptation scenarios must be compared to the no action scenario (see Equation

1). With this comparison, our results suggest that the NPV for both Integrated and Reactive are positive, with a preference for the Integrated approach.

Caveats and their implications

Given the timeframe and resources available, it was not possible to carry out a comprehensive analysis of all possible adaptation options. Rather, this is an initial attempt to examine realistic adaptation approaches that are currently under consideration in Belize and highlight the potential for this methodology to inform the decision-making process. The limitations of the current study should be considered and have proven useful in highlighting next steps for this work (see Opportunities for Future Work).

One of the main limitations of the current study relates to the scenario comparisons. The storylines used in the current study are based on differing levels of development. For example, the storyline for scenarios 3 and 4 suggests that coastal development increases dramatically in the South Central region, and we therefore increased development throughout the region. The Reactive approach assumes that the adaptation options put into place are reactive to the level of development. We then compare this scenario to one where there is no reactive management, but also the level of development is lower. An interesting extension of this would be to compare No Action and Reactive approaches under the same level of development. This would likely considerably increase the damages associated with No Action. Likewise, it would be useful to compare all three approaches (No Action, Integrated Adaptation and Reactive) under lower levels of development. Table 8 shows the matrix of possible scenarios, with x marking the scenarios modeled in the current study.

Table 8. Possible scenarios for analysis. X marks the scenarios modeled in the current study.

	Coastal Zone Planning Scenario		
Adaptation Approach	Current	Informed management	Development
No Action	x		
Integrated		x	
Reactive			x

In all the scenarios we modeled, we included costs of implementing adaptation measures (seawalls, MPA, mangrove restoration and private reserves) and we are confident our costs are based on the best available information. However, additional costs of development and coastal zone management (especially those related to changes in the zoning and implementation of other human activities such as aquaculture, oil exploration, and marine transportation) that did not directly relate to the green and grey measures were not considered. We hope to build on this analysis by researching these additional costs and including them in future work.

As with any modeling of potential futures, there is a level of uncertainty. An important caveat to consider with the current study is that we were unable to include the direct impacts of climate change on recreation due to an absence of data to inform these relationships. Our results make clear that recreation is a major contributor to the NPV of services in Belize and the NPV of the alternative adaptation options. Thus this analysis was particularly useful for indicating an area of uncertainty that requires future attention and funding: the impacts of climate change on tourism and recreation. Given the complexity of this problem, it is unclear how the impacts of climate on recreation would have changed the outcome – highlighting another reason why this problem deserves future research and attention.

Influence on Decision Making

This study is timely and relevant to the decisions being made by the Belizean government today as it reviews and votes on a nationally binding Integrated Coastal Zone Management Plan (ICZMP) with region-specific spatial planning and guidance. The Coastal Zone Management Authority and Institute (CZMAI) has reviewed and approved our selected ecosystem services, cost-benefit analysis approach, and climate and adaptation scenarios. While the results of this particular analysis are too preliminary to include in the final legislation (which has been in development for the last three years), climate adaptation is an issue for national action highlighted in the ICZMP. Our hope, and that of CZMAI, is that the results presented here are a starting point for future analysis that would be incorporated into the plan during its revision every four years.

In the meantime, the Belizean government has recently submitted a proposal for the Adaptation Fund to implement priority ecosystem-based marine conservation and climate adaptation measures to strengthen climate resilience of the Belize Barrier Reef System and its productive marine resources. The Adaptation Fund proposal includes a focus on the area of Placencia Peninsula, and the results of the present study can be used immediately to inform uses of the Fund.

In addition, government representatives and academics that attended the Belize City workshop on climate adaptation will receive the results of the study and have indicated an interest in applying these approaches to decisions about coastal planning and disaster risk reduction in Barbados and Jamaica. We also anticipate publishing the study in the scientific literature to make the methods and results available more broadly to researchers and policymakers.

Opportunities for Future Analysis

CLIMATE IMPACTS ON SERVICES

- Tourism/reaction
- Carbon storage and sequestration

Note that we modeled the influence of climate adaptation strategies on all four services, but were only able to model the impact of climate change on two of the four services – lobster fisheries and coastal protection. With further support and time we would be able to conceptualize climate impacts on the other two services and implement new model functionality.

CLIMATE IMPACTS ON HABITATS

- Mangroves
- Coral reefs

SOCIO-ECONOMIC COMPONENTS OF SCENARIOS

- Property value
- Population

DEVELOPMENT OF NEAR-TERM CLIMATE SCENARIOS

- 2030s

EXPANDING CLIMATE SCENARIOS

- Freshwater
- Ocean acidification
- Storm intensity and frequency

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Appendix 1 – Detailed Methods for InVEST Models

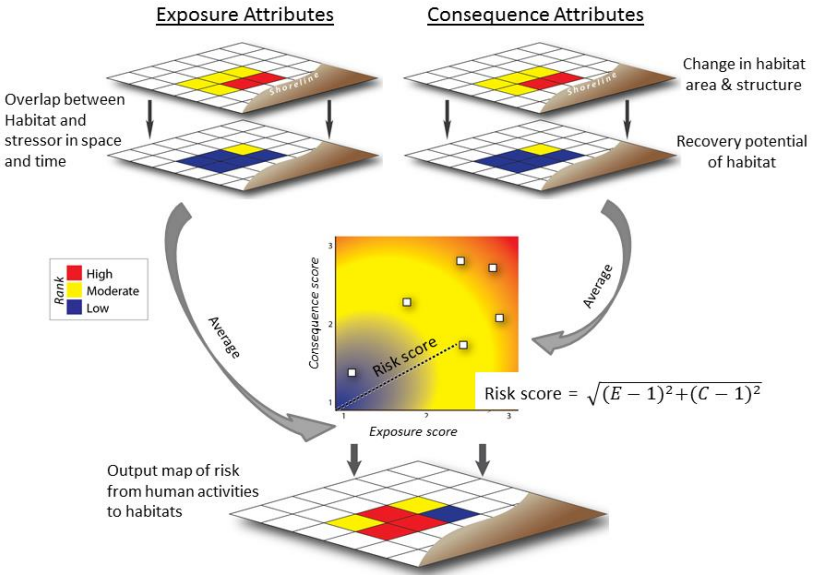
HABITAT RISK ASSESSMENT

Summary

The condition of coastal habitats is a key determinant of the ecosystem services they can provide. Human activities, such as fishing, climate change, and coastal development, may degrade coastal habitats and hamper the provisioning of valuable goods and services that people want and need. As human activities continue to intensify, so too does the need for quick, clear and repeatable ways of assessing the risks posed by human activities under various management plans. The InVEST habitat risk assessment (HRA) model allows users to assess the risk posed to coastal and marine habitats by human activities and the potential consequences for delivery of ecosystem services. Risk is a function of the exposure of each habitat to each activity and the consequences for each particular habitat type. Exposure to stressors can arise through overlap in space and time. Consequence depends on the effects of activities on habitat area and density, and the ability of habitats to recover from these effects. Outputs from the model are useful for understanding the relative risk of human activities and climate change to habitats within a study region and among alternative future scenarios. Model outputs can help identify areas on the seascape where human activities may create trade-offs among environmental services by posing risk high enough to compromise habitat structure and function. The model can help to prioritize areas for conservation and inform the design and configuration of spatial plans.

How the model works

The HRA model combines information about the exposure of habitats to each human activity with information about the consequence of that exposure to produce maps of risk to habitats and habitat quality for provisioning of each service. Exposure depends on the extent of geographic overlap between habitats and human activities, the duration of time that the activity and habitat overlap, the intensity of the stressor and the degree to which management strategies mitigate impact. The consequence depends on the degree of habitat loss, change in habitat structure and the ability of habitats to recover from these effects (i.e., through life history traits such as recruitment and regeneration rates). The first step in the model determines habitat exposure and consequence by assigning a score of HIGH, MEDIUM or LOW to a standardized set of criteria. The model automatically assigns the scores for spatial overlap using input data layers on the location and extent of habitats and human activities. To ensure transparency, the other scores are determined based on readily available data from the scientific literature and published reports. Guidelines for scoring each criterion are provided in the InVEST User Guide (Tallis et al 2012). The second step in the model combines the exposure and consequence values to produce a risk value for each human activity-habitat combination. Risk to habitat in each grid cell of the area of interest is calculated as the Euclidean distance from the origin in the exposure-consequence space (Fig. 1, Tallis et al 2012). In the third step, the model quantifies the cumulative risk of all stressors on the habitats, assigns a qualitative risk (High, Medium and Low) to each grid cell of habitat and calculates a total ecosystem risk score of all stressors on all habitats combined. In the fourth and final step, the qualitative risk scores are translated into habitat quality scores which are then used as inputs into the ecosystem service models. In general, the higher the risk, the more fragmented the habitat and the lower the risk the more intact the habitat (but see individual model descriptions of habitat quality inputs).



Appendix 1, Figure 1. Conceptual model of the Habitat Risk

Appendix 1, Table 1. Description of input data for the Habitat Risk Assessment in Belize

INPUT	SOURCE	HOW THE DATA WERE USED IN THE MODEL
Coral	CZMAI and Peter Mumby	These data were used to determine the location and extent of coral exposed to human activities
Mangroves	World Wildlife Fund	These data were used to determine the location and extent of mangroves exposed to human activities
Seagrass	CZMAI	These data were used to determine the location and extent of seagrass exposed to human activities
Aquaculture zone	Fisheries Department, Department of Economics and CZMAI	These data were used to determine the spatial overlap between aquaculture and coastal habitats.
Agriculture run-off zone	World Research Institute and CZMAI	These data were used to determine the spatial overlap between agricultural run-off and coastal habitats.
Coastal development zone	Natural Capital Project – The InSEAM Annotation Tool, Department of Environment, Jan Meerman (Biodiversity and Environmental Resource Data System of Belize - Belize Tropical Forest Studies) and CZMAI	These data were used to determine the spatial overlap between coastal development and coastal habitats.
Dredging zone	Mining Department and CZMAI	These data were used to determine the spatial overlap between dredging and coastal habitats.
Fishing zone	Fisheries Department and CZMAI	These data were used to determine the spatial overlap between fishing and coastal habitats.
Marine transportation zone	Belize Port Authority and CZMAI	These data were used to determine the spatial overlap between marine transportation and coastal habitats.
Oil exploration/drilling zone	Department of Geology and Petroleum and CZMAI	These data were used to determine the spatial overlap between oil exploration/drilling and coastal habitats.
Effects of human activities on coastal habitats	Habitat-stressor ratings table with scores based on review of the scientific literature (see Table X).	These data are used to assess additional attributes of habitat exposure to human activities (e.g., in time and based on management effectiveness). They are also used to assess the consequences of that exposure for change in habitat structure and area and the ability of the habitat to recovery from stress based on life history characteristics such as natural mortality, recruitment and connectivity.

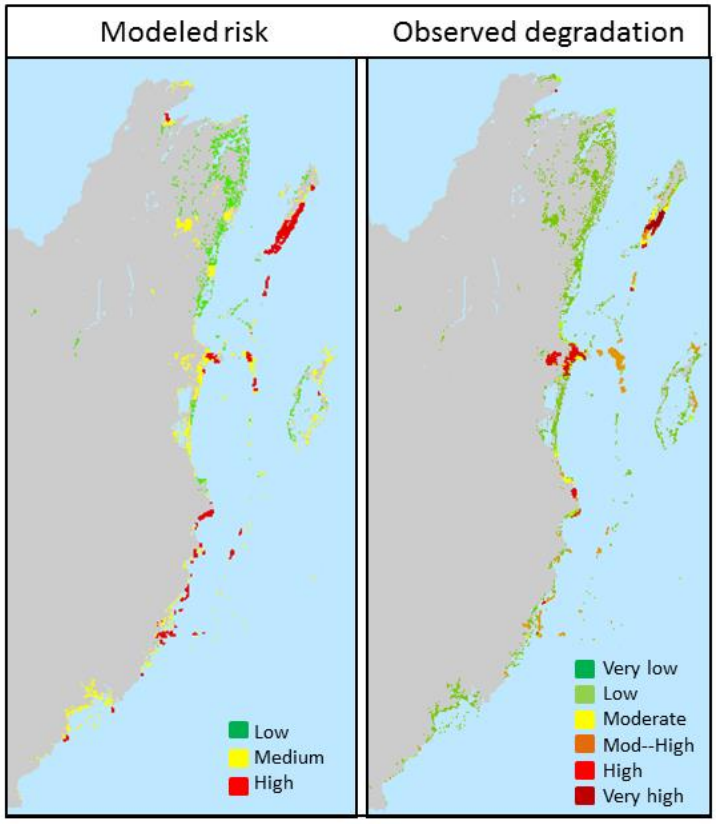
In Belize we used the HRA model to assess risk to habitats posed by both current and potential future uses of the coastal and marine environment. We quantified the risk to three main habitat types - coral, mangrove and seagrass – based on the coastal zone planning process which includes nine different human activities (e.g., marine transportation, coastal development etc. Appendix 1, Table 1) at a 500 m resolution. The nine activities align with the zones for the Belize Integrated Coastal Zone Management Plan (CZMP). These zones were identified through our collaboration with the Coastal Zone Management Authority, and extensive stakeholder engagement. For this climate adaptation study, we used the HRA model to evaluate risk to habitats under one current and three alternative future management scenarios -- No Action, Integrated, and Reactive, which are based on the CZMP scenarios -- Current, Informed Management, and Development, respectively. The types of model inputs were the same for all scenario runs; however, the location, magnitude and extent of human activities varied depending on the management scenario. Note that the HRA model does not assess climate change impacts on habitats.

Appendix 1, Table 2. Description of outputs from Habitat Risk Assessment

OUTPUT	DESCRIPTION
Qualitative habitat risk	Locations where each habitat type (e.g., coral, mangroves, seagrass) is at High, Medium and Low risk to all human activities included in the model
Ecosystem risk	The sum of all cumulative risk scores for all habitats in each grid cell. For example, in a nearshore grid cell that contains some coral reef, mangrove and seagrass, the ecosystem risk value reflects the risk to all three habitats in the cell. The ecosystem risk value increases as the number of habitats in a cell exposed to stressors increases.

Model validation

We tested the ability of the HRA model to capture observed habitat degradation by comparing our results for mangrove risk hotspots to observed data on mangrove fragmentation along the entire coast of Belize. The HRA model produces three categories of risk (High, Medium and Low) and the observed data categorize mangroves in five fragmentation categories (from Highest to Lowest). We found that the HRA model identified as high risk those areas where mangrove fragmentation is highest (e.g., Ambergris Caye, Belize City, Placencia) and identified as low risk much of the coastline where mangrove fragmentation is qualitatively lower (e.g., Northern Region and east coast of Turneffe Atoll). While we have not tested the ability of the model to accurately forecast risk of human activities to coral and seagrass, the qualitatively similar results for modeled risk to mangroves and observed fragmentation suggests the utility of the model for other habitats.



Appendix 1, Figure 2. Comparison of modeled mangrove risk to observed mangrove degradation.

Limitations and assumptions

- Results should be interpreted on a relative scale within a study region and across habitats and stressors, but not to results from separate analyses.
- Results do not reflect the effects of past human activities.
- Results are based on equal weighting of criteria unless the user weights the criteria by importance or data quality.
- Cumulative risk is additive (rather than synergistic or antagonistic).

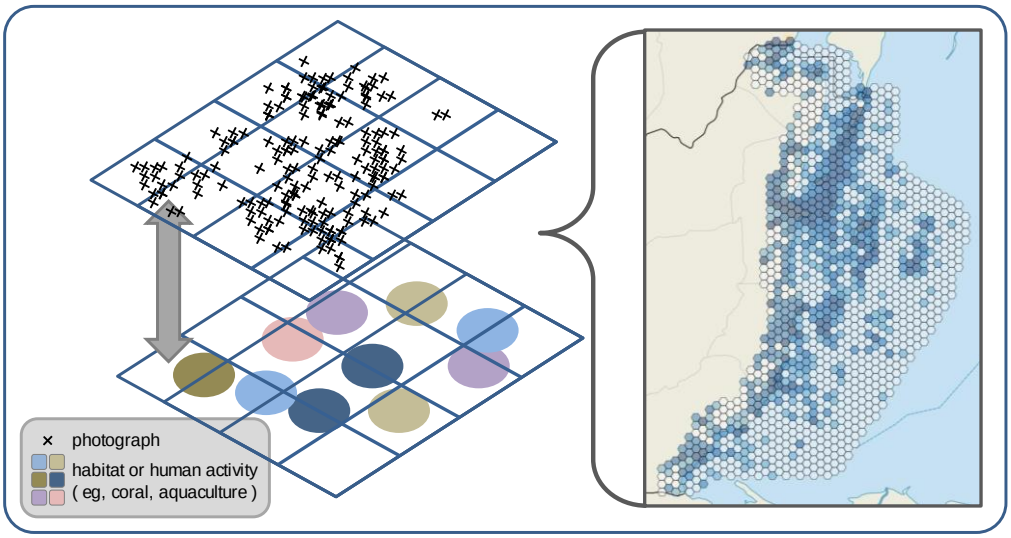
RECREATION

Summary

People's decisions about where to recreate are influenced by the environment. Recreational divers need suitable water quality; birders seek out sites with high biodiversity. Through its contribution to outdoor recreation, the environment provides services to people. To quantify this value of natural environments, the InVEST recreation model predicts the spread of person-days of recreation by tourists in the coastal zone. The spread is based on the locations of marine habitats and human activities, such as fishing or transportation, that factor into decisions people make about where to recreate. Behind the scenes, the tool estimates the contribution of activities and environment (e.g., mangroves, fishing) to visitation rate using a simple linear regression analysis. Because we lack empirical data on visitation to most locations, we parameterize the model using a proxy for visitation: geo-tagged photographs posted to the website flickr. Using these estimates, the model can predict how future changes to habitats and patterns of human use will alter visitation rates. Outputs from tool are maps showing current patterns of recreational use and future patterns of use under alternate scenarios.

How the model works

First we conducted an initial run of the model to estimate the degree to which each attribute (e.g., coral habitat, mangrove habitat, transportation corridors; see below) relates to current visitation in the coastal zone of Belize, which we divided into 1268 hexagonal grid cells (width of 5 km between edges). Since fine-scale data on numbers of visitors is limited to a few locations (e.g., archaeological sites and marine reserves), we assumed that current visitation can be approximated by the total number of annual person-days of photographs uploaded to the photo-sharing website Flickr. Many of the photographs in Flickr have been assigned to a specific latitude/longitude. Using this location, along with the photographer's user name and date that the image was taken, the tool can compute the total annual days that a user took at least one photograph within each cell. The values of photo-person-days across all cells are regressed against the percent coverage of all attributes within each grid cell (current visitation rates and attribute coverage data are log transformed). The model estimates the extent to which visitation depends on all the input variables. For example, the model estimated that coral reefs and coastal development tend to draw visitors, as reefs are desirable to visit and tourists need infrastructure for lodging and to facilitate travel.



Appendix 1, Figure 3. The model uses the relationships between locations of geo-tagged photographs and coverage of natural habitats and human activities to predict where in Belize tourists will visit. Darker polygons indicate more visitors.

In subsequent model runs, the tool employs the regression coefficients (beta values) computed in the initial model run to predict visitation, given a spatial configuration of the predictors (e.g., coral reefs, coastal development etc., see Appendix 1, Table 3 for input data). We used outputs from the Habitat Risk Assessment for the current and three possible future zoning schemes to determine where coral reef, mangrove and seagrass habitats were high enough quality to support tourism. We assumed that areas of habitat at high risk were too degraded to provide tourism and recreation opportunities and so removed these areas from the input maps to the recreation model. Areas of low risk were treated as fully functional habitats. Where habitats were at medium risk, we assumed only 50 % of the habitat area in each grid cell was capable of drawing visitors. We then ran the model to predict percent of total visitation to each grid cell under the current and three future climate adaptation scenarios (i.e., No Action, Integrated and Reactive).

We normalized the predicted visitation to each cell by dividing the total number of person-days across all cells. To estimate the total number of person-days to each cell for the current situation, we multiplied the proportion of person-days by 2,807,823. This value is based on the total number of incoming cruise (764,628) and overnight (238,691) visitors reported by the Belize Tourism Bureau in 2010 and the assumption that overnight visitors spend 8.56 days and cruise tourists spend 1 day in the country (APAMO, Kwan et al. 2010, National Sustainable Tourism Master Plan for Belize 2030, UNCTAD Handbook of Statistics). A multiplier of 0.74 was also included to discount total visitation to Belize by the proportion of person-days that tourists spend in the coastal zone (based on the proportion of all photo-person-days in the Flickr database that fall within the coastal zone), such that

Total person-day = (annual overnight visitors * 8.56) + (annual cruise visitors*1)]*0.74 (Eq. 1)

Appendix 1,Table 3. Description of input data for the recreation model in Belize.

INPUT	SOURCE	HOW THE DATA WERE USED IN THE MODEL
Photo-user-days	Total number of annual person-days of photographs uploaded to the photo-sharing website flickr from 2005—2012 Natural Capital Project	These data are used to parameterize the model. They allow us to estimate the significance and effect of each of the human use activities (see list of zones below) on visitation.
Land vs. ocean	CZMAI	These data were used to estimate the effect of land and ocean on current visitation and to predict future visitation.
Coral	CZMAI and Peter Mumby	These data were used to estimate the effect of coral reefs on current visitation and to predict future visitation.
Mangroves	World Wildlife Fund	These data were used to estimate the effect of mangroves on current visitation and to predict future visitation.
Seagrass	CZMAI	These data were used to estimate the effect of seagrass on current visitation and to predict future visitation.
Aquaculture zone	Fisheries Department, Department of Economics and CZMAI	These data were used to estimate the effect of aquaculture on current visitation and to predict future visitation.
Agriculture zone	Jan Meerman (Biodiversity and Environmental Resource Data System of Belize - Belize Tropical Forest Studies) and CZMAI	These data were used to estimate the effect of agriculture on current visitation and to predict future visitation.
Agriculture run-off zone	World Research Institute and CZMAI	These data were used to estimate the effect of agricultural run-off on current visitation and to predict future visitation.
Coastal development zone	NATCAP Project – The InSEAM Annotation Tool, Department of Environment, Jan Meerman (Biodiversity and Environmental Resource Data System of Belize - Belize Tropical Forest Studies) and CZMAI	These data were used to estimate the effect of coastal development on current visitation and to predict future visitation.
Dredging zone	Mining Department and CZMAI	These data were used to estimate the effect of dredging on current visitation and to predict future visitation.
Fishing zone	Fisheries Department and CZMAI	These data were used to estimate the effect of fishing on current visitation and to predict future visitation.
Marine transportation zone	Belize Port Authority and CZMAI	These data were used to estimate the effect of marine transportation on current visitation and to predict future visitation.
Oil exploration/drilling zone	Department of Geology and Petroleum and CZMAI	These data were used to estimate the effect of oil exploration/drilling on current visitation and to predict future visitation.

To estimate the total number of person-days to each cell for the Integrated scenario, we used a similar approach. Since the configuration of human uses in the Integrated scenario follows the recommendation by the National Sustainable Tourism Master Plan for Belize, we calculated the total number of person-days per cell using estimates for future visitation to Belize from this plan. According to the National Sustainable Tourism Master Plan, Belize can expect to receive 1,500,000 cruise tourists and 556,000 overnight tourists if the Plan is implemented. The average length of a stay will also increase to 10.6 days per trip. Substituting these values into Eq. 1, the National Sustainable Tourism Master Plan for Belize predicts a total of 7,393,600 person-days by tourists in 2030. If visitation increases linearly between 2010-2030 there will be 6,247,156 total

person-days in 2025. Thus, we calculated the total number of person-days to each cell for the Integrated scenario by multiplying 6,247,156 by the proportional visitation rate.

For the No Action and Reactive scenarios, we estimated the total person-days using a similar approach which assumes that tourists will spend 4,806,187 in Belize in the year 2025. This is based on the long-term trend in visitation from 1995-2010 (Belize Tourism Board pers. comm. 2012), and the value corresponds with the prediction by the National Sustainable Tourism Master Plan for 3,935,961 person-days in 2020 if the National Sustainable Tourism Plan is not implemented.

Appendix 1, Table 4. Description of output data for the recreation model in Belize.

OUTPUT	DESCRIPTION
Percent of visitors	Proportion of annual person-days of recreation by tourists in 5 km grid-cells spanning the entire coastal and marine zone of Belize. Total annual person-days is defined as the number of days of recreation by any person in a location each year.
Total number of visitors	The total number of person-days in a 5 km grid cell based on percent of visitors to that grid cell and total number of visitors to Belize.
Revenue from visitors	The revenue from visitors to a grid cell based on the total number of person-days in a 5 km grid cell and estimates of expenditures per-person per-day in Belize.

To estimate expenditures by tourists, for each cell we first apportioned total person-days into overnight and cruise visitors, then multiplied each value by the average daily expenditure rates provided by the National Sustainable Tourism Master Plan. Current (2008) expenditures are reportedly USD $133/day and $57/day for overnight and cruise visitors, respectively. Assuming that expenditures increase linearly until 2030, the National Sustainable Tourism Master Plan predicts tourists will spend USD $195/day and $83/day in 2025 under the Informed Management scenario. For the Conservation and Development scenarios, expenditures were determined using the same method as visitation by projecting expenditures provided by the National Sustainable Tourism Master Plan (from 2000-2008) ahead to the year 2025.

Model validation

The number of tourists who visit a location is related to the number of photographs taken in the same area and uploaded to the online database Flickr. This relationship, between the proportion of actual user-days and the proportion of photo-user-days, has been validated using data from 715 tourist attractions worldwide (Wood et al. in prep.). Note, because the model does not presuppose that any predictor variable has an effect on visitation, it is not necessary to validate their effects. Instead, the tool estimates the magnitude of each predictor's effect based on its spatial correspondence with current visitation in Belize.

Limitations and assumptions

- The model assumes that people will respond similarly in the future to the attributes that serve as predictors in the model. In other words, the assumption is that people in the future will continue to be drawn to or repelled by a given attributes to the same degree as currently.
- Some of the attributes that are used as predictors of visitation are representations of areas managed for particular human use (e.g. transportation). The model assumes that future management of the zones and the type of activities that they represent are similar to current.
- Since there are no fine-scale data on the distribution of visitors to Belize, we use photo-person-days as a proxy for the relative density of actual person-days of recreation across the coastal zone.

LOBSTER

Summary of model

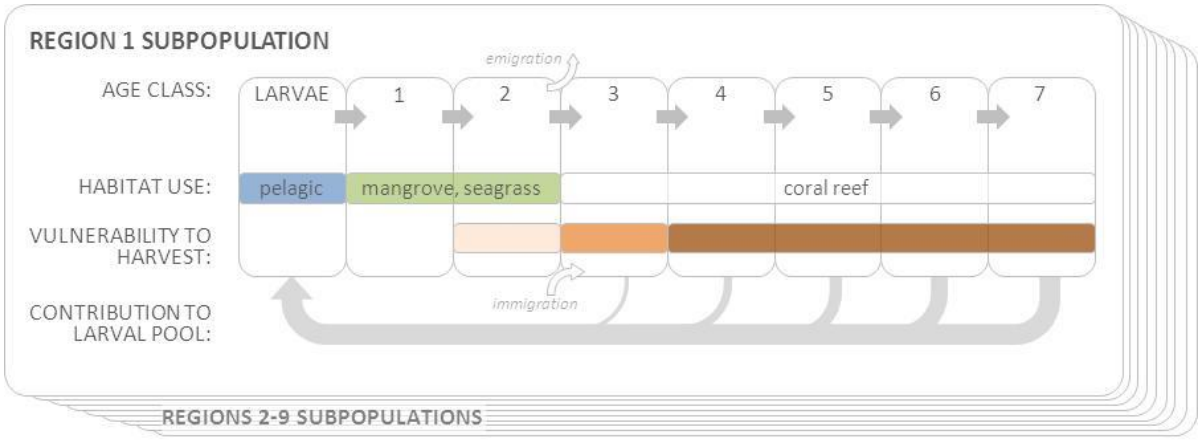
Caribbean spiny lobster (*Panulirus argus*) are a heavily harvested, commercially important and widespread species that is found from Bermuda to Brazil. The model described here represents the Belizean population and can be used to explore how it responds to changes in amount of lobster habitat (i.e., seagrass, mangrove, coral reef) or in fishing pressure.

Primary model outputs are gross export revenue and harvest of lobster tail.

How the model works

The population is modeled as 9 regional, linked subpopulations (one per Belize Coastal Zone Management Planning Region) connected via immigration as lobster move from mangroves and seagrasses to coral reefs.

Appendix 1, Figure 4. Conceptual diagram of lobster model.



An age-structured model with Beverton-Holt recruitment is used to model the population from 2011-2050 on an annual time-step. Initial conditions are based on the amounts of mangrove and seagrass (for larvae and juveniles), and coral reef (for adults) in each planning region. Population dynamics are given by:

Where is the number of lobster of age *a* (*A* = maximum age = 7) in planning region *x* at the start of year *y,* is lobster catch (numbers). Spawner biomass, , is a function of numbers of lobster in each region, maturity (using a maturity ogive), and weight at age (using von Bertalanffy growth). are stock-recruitment relationship parameters. is survival from natural mortality from *a*-1 to *a* (note: is settlement survival from the larval, pelagic stage):

Where is baseline survival from *a*-1 to *a*: , and if a>0; is the natural mortality rate from *a*-1 to *a.* indicates if a transition to a new habitat happens from *a*-1 to *a,* which is used so that changes in habitat coverage only affect lobster survival during transition to that habitat, but not once settled in the habitat. is the amount of habitat *h* (e.g., coral, mangrove, seagrass) in the region in the baseline (*BL;* i.e., status quo) system or under the scenario being evaluated (*SCEN).* is the degree to which survival during the transition from *a*-1 to *a* depends upon availability of *h,* is a shape parameter, and is the number of habitats with a parameter.

The harvest in numbers for each age are removed from biomass vulnerable to harvest as: ; where exploitation rate is: . is year 2010 harvest in pounds, is harvestable year 2010 biomass , is % change in fishing effort from baseline, and is vulnerability to harvest. Harvest in pounds is the exploitation rate applied to biomass vulnerable to harvest.

Gross export revenue in a region in year 2025 is based on proportion of harvest that is exported, the product stream (tail or head meat) and price per pound of each product stream as:

where is the proportion of harvest that is exported, is the conversion factor to scale a whole lobster to a processed one (sum of tail and head meat), is price per pound of tail or head meat, and is proportion of processed harvest that is tail meat.

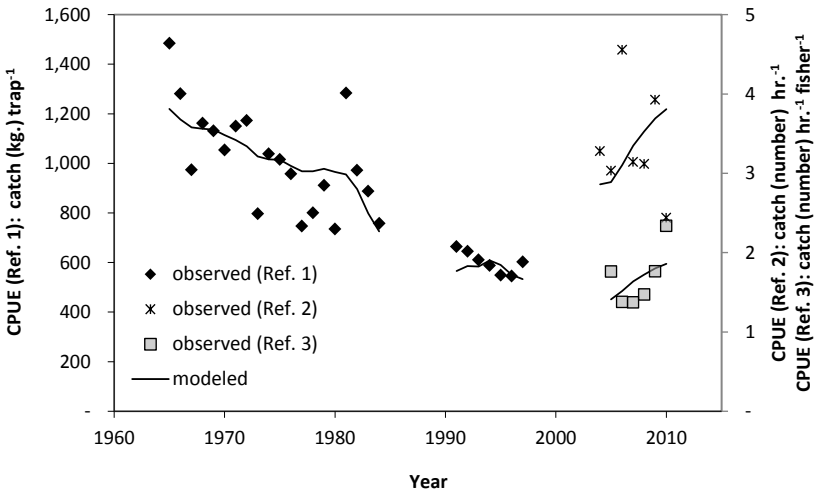
To inform the design of the Belize CZM plan, we quantified national catch and revenue in 2010 (current scenario) and for the three possible future (2025) zoning schemes. All inputs into the model remained constant for each scenario except for the amount of adult and nursery habitat (i.e., coral reefs, mangroves and seagrass) for lobster and changes in fishing locations based on the Belize Coastal Zone Management planning process. We used outputs from the Habitat Risk Assessment model for the current and three future scenarios as inputs into the lobster fishery model. Where habitats were at high risk, we assumed they were too degraded to provide nursery and adult habitat for lobster. In contrast, we assumed that 100% of low risk habitat and 50% of medium risk habitat was capable of supporting lobster, respectively. We then quantified the area of coral, mangroves and seagrass capable of providing nursery and adult habitat in each planning region and used this as inputs into the model described above.

Appendix 1, Table 5. Description of input data for lobster model in Belize.

INPUT	SOURCE	HOW THE DATA WERE USED IN THE MODEL
Lobster growth parameters	Literature values (Refs* 1-3) and fitting (e.g., stock-recruit parameters fit to steepness and initial recruitment).	A variety of parameters are used in the population dynamics model to determine the rate of growth of the lobster population. Parameters include those for: natural mortality rate, the maturity function, stock-recruit relationship, von Bertalanffy growth function, weight-length relationship, initial recruitment.
Lobster-habitat associations	User-defined based on literature values	Parameters are used to identify which ages are linked to which habitat types, the strength of those dependencies, and when a transition to a new habitat occurs.
Habitat coverage	Calculated in ArcGIS	Areal extent of mangroves, seagrasses and coral reefs in each planning region is used to determine amount of larval and juvenile settlement in each region, and immigration between planning regions. Change in habitat coverage (via scenarios) affects lobster survival.
Fishery operations	User-defined, legal harvest requirements (e.g., minimum harvestable size)	Parameters that define fishing effort, age-specific vulnerability to and selectivity of harvest are used to calculate the volume and amount of lobster harvest.
Market operations	Belize Fisheries Dept. Annual Reports (2007&2008): http://www.agriculture.gov.bz/Document_Center.html	Market operation parameters are used to determine the product stream that the harvested lobster enters and express harvest in monetary terms, as gross export revenue. Parameters include: proportion of harvest that is tail or head meat, proportion of harvest that is exported, a conversion factor between whole and processed lobster weight, prices per pound (tail and head meat).

References: 1) M.E. de Leon González, R.G. Carrasco and R.A. Carcamo. 2008. A Cohort Analysis of Spiny Lobster from Belize; 2) Little, S.A. and W.H. Watson III. 2005. Differences in the size at maturity of female american lobsters, *Homarus americanus*, captured throughout the range of the offshore fishery. J. Crust. Biol. 25(4): 585-592; 3) Puga, R., Hernández S., López J and León M.E. de. 2005. Bioeconomic modeling and risk assessment of the Cuban fishery for spiny lobster *Panulirus argus*, Fisheries Research 75: 149–163.

Validation or model testing. Appropriate estimates of the 2 stock-recruit parameters and the initial, pre-exploitation recruitment are critical for use of a model of this type. All 3 were estimated using by fitting to 3 time series of local catch-per-unit-effort (CPUE; model fit shown in Figure 2). Data sources for other model parameters were taken from regional literature values to ensure that the model best represents the Belizean population. A reasonable estimate of current population size (year 2010 in this model) is an important starting point for modeling future population size. The pre-2010 population was modeled using a catch time series of 1932-2010 landings, generated by inflating annual lobster tail landings (sources: Ministry of Agriculture and Fisheries', 2008 Annual Report; Fisheries Department statistics) to account for head meat, and converting from processed to whole lobster weight.



Appendix 1, Figure 5. Model fit to 3 time series of catch-per-unit-effort (CPUE).

Ref.1: A. Carcamo, Jr, R.A. 2002. Report on the spiny lobster fisheries of Belize. in: Second Workshop on the Management of Caribbean Spiny Lobster Fisheries in the WECAFC Area. FAO Fisheries Report No. 715.; Ref. 2: Long Term Atoll Monitoring Program (LAMP) fishery independent surveys at SCMR, Glover's, GSSCMR and LBCNP.; Ref. 3. Glover's Reef Atoll Fisheries Catch Data Collection Program, described in "Glover's

OUTPUT	DESCRIPTION
Harvest (pounds)	This output is the total pounds of the tail portion of lobster harvested for each planning region in the year 2025
Gross export revenue (BZ$)	This output is the gross export revenue generated from lobster harvest (see previous output) for each planning region in the year 2025. The revenue is for the tail meat only.

Appendix 1, Table 6. Description of outputs from lobster model. Outputs can be produced for any year in the model run, but default outputs are for the end of the model run (i.e., year 2050), after the model has had time to equilibrate.

Limitations and assumptions

- Population growth parameters are nationwide, not region-specific
- Habitat dependencies are obligatory (e.g., habitat substitutability is not explicit represented).
- The population responds to change in habitat quantity (i.e., areal extent of mangrove, seagrass, and coral reef), not quality of those habitats.
- The fishery is assumed to take place at the start of the year, before natural mortality
- The model assumes near knife-edge selectivity in harvest function
- Harvest selectivity (and catchabilitiy) is invariant, such that technological improvements to gear or changes in fishing practices are not modeled.
- Market operations are fixed, such that they do not vary in response to amount of harvest, shifts in market or consumer preference, or technological changes.

COASTAL PROTECTION

Summary

The InVEST Coastal Protection model produces an estimate of wave attenuation and reduction in shoreline erosion provided by coastal and marine habitats. 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 and scenarios. For sandy beaches, the model computes the difference in shoreline retreat before and after habitat modification. For muddy beds, the model computes the volume of sediment loss and the distance inland from the shoreline where sedimentlosses occurs. Using predicted values for erosion, the length of the shoreline, and property values, 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 these 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. In addition to quantifying natural coastal protection services, the model also estimates the height of seawall needed to protect coastal land from erosion under different sea level rise and storm scenarios.

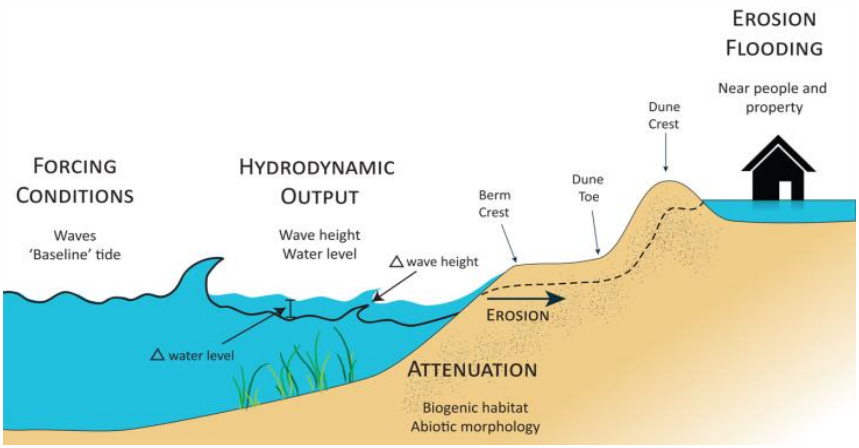
How the model works

The evolution of wave height from offshore to the shoreline follows the well-established wave equation:

$$\frac{1}{8}\rho g \frac{\partial C_g H^2}{\partial x} = -D_{break} - D_{bottom} - D_{veg}$$

where ρ=1,024 kg/m^3 is the density of seawater, g=9.81 m/s^2 is the gravitational acceleration, H is the wave height, C_g is the speed at which wave energy travels. D_{break}, D_{bottom}, and D_{veg} represent the dissipation of wave energy due to wave breaking, bottom friction, and the presence of submerged vegetation, respectively.

Wave energy dissipation due to vegetation is directly proportional to habitat density, submerged height and stem diameter. Coral reefs act somewhat differently; their structural presence induces wave dissipation due to breaking and dissipate wave energy because of bottom friction. If coral reefs die, bottom friction along the reef top is reduced leading to less wave dissipation.



Appendix 1, Figure 6. Physical processes captured in the wave and erosion model. By dissipating wave energy, or reducing wave height, and by reducing the water level in the nearshore region, the presence of healthy natural habitats leads to less

The model of erosion for muddy consolidated beds assumes that the mobilization of sediment occurs above some threshold of wave-induced forcing on the seabed. Since this bed forcing is proportional to wave height, greater volumes of sediment are expected to be eroded. The distance inland from the shoreline where erosion occurs will be greater for larger wave heights propagating over land. The model for sandy beaches estimates shoreline retreat in the absence of habitat using published approaches (see Coastal protection chapter in Tallis et al 2012 for review of these approaches). To estimate the difference in erosion owing to the presence of habitat, the model computes the average ratio of wave-induced water level and wave dissipation with and without habitat; these ratios are multiplied by the computed beach retreat to estimate the reduction in retreat due to the presence of natural habitat.

The model values the protection provided by habitats in terms of the avoided damages to property due to erosion from waves. The model estimates damages due to loss of land from a single storm event as:

$D_x = E_x V$ where is area eroded under each scenario, x={1,2} and V is the total property value (land and structures). Because storms occur at irregular intervals over time (and vary in strength and probability of occurrence), the model allows the user to assess these benefits across a defined time horizon for a given sized storm with an expected frequency. As changes in land use need to be considered against other possible investments and time preferences, the model considers the expected present value, *EPV*, of services provided by habitat. The calculation employs a discount rate, *i*, over a user-defined time horizon, τ, expressed in years. It reflects the value of the stream of avoided storm damages over time due to a change in habitat and discounts the value of those avoided damages in distant periods when the discount rate is greater than zero. *EPV* for a given storm class is calculated as:

where D_A is the avoided damage for a given storm class with an expected return time of *T*.

$$EPV = \sum_{t=1}^{\tau} \frac{pD_A}{(1+i)^t}$$

In Belize we used the InVEST coastal protection model to quantify and value the protection provided by coral reefs, mangroves and seagrass beds currently, and under the current and three possible future scenarios (i.e., No Action, Integrated and Reactive). We modeled wave attenuation and erosion for the mainland and large atolls and large cayes by dividing the coastline into over 400 segments ranging in length from a few hundred to a few thousand meters. The segments differed in the extent of mangroves, corals and seagrass defending the coastline, exposure to storms, and development. For each coastline segment we modeled wave attenuation and erosion for the largest hurricane (either category 1 or 2) with a return period of less than 10 years (so that our analysis would be relevant to the 2025 time horizon of the planning process). We used observed wave heights, surge and return periods from the Storm Hazard Assessment for Belize. We valued 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 now and 2100,we used the avoided damages per storm event and the probability of a storm of that size occurring each year during this time horizon (see equation for EPV above).

We estimated the land protected and avoided damages provided by corals, mangroves and seagrasses currently, and under the three possible future management scenarios. All physical and oceanographic data were the same in the four scenarios, but the biological information and amount of coastal development differed between the Current, No Action, Integrated and Reactive scenarios. We used the outputs from the Habitat Risk Assessment model for the four scenarios to identify areas of habitat that were too degraded to provide protection. We assumed that habitats at high risk were unable to attenuate waves, and that habitats at low risk were fully functional. Where mangroves and seagrass were at medium risk, we halved the density of trunks and shoots. Where coral reefs were at medium risk, we halved the friction factor of the reef, a parameter that influences wave attenuation. We then fed the habitat information into the model as described above to produce outputs for the current and four possible future zoning schemes.

Appendix 1, Table 7. 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 Mumby	Barrier coral reefs are one of the four habitat types in the coastal hazard index that determines exposure to erosion and flooding. Rank 2 and protective distance 30 kilometers.
Mangrove	World Wildlife Fund	Mangrove forests are one of the four habitat types in the coastal hazard index that determines exposure to erosion and flooding. Rank 1 and protective distance 500 meters.
Seagrass	CZMAI	Seagrass beds are one of the four habitat types in the coastal hazard index that determines exposure to erosion and flooding. Rank 4 and protective distance 500 meters.
Seagrass and Mangrove Physical Parameters	Literature survey (see InVEST User Guide)	These physical parameters (diameter, height, and density of seagrass stems and mangrove trunks, 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 width 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 Hazard 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 Hazard Assessment for Belize; Coastal Engineering Manual (2008); measured fetch lengths; average depths.	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.
Human population	Statistical Institute of Belize; Biodiversity and Environmental Resource Data System of Belize (BERDS)	These data allow us to assess 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.

Estimating seawall height

Though seawalls are constructed to provide protection from inundation and wave attack, there are still potential hazards in areas protected by seawalls. Water can overtop the wall if the water surface due to storm surge, tides, and sea level rise exceeds the seawall crest elevation or if the water surface is below the crest of the wall but the wave characteristics are such that wave run-up intermittently overtops the structure.

There are empirical equations that yield an overtopping rate, *q*, based on the height of the seawall (C_{el}), the water depth (h_s) and the wave height at the toe of the seawall (H_s), and the peak wave period (T_p). In order to design a seawall, one must fix the overtopping rate to a safe level for the design storm characteristics. The maximum overtopping rate permissible before safety becomes a concern is: . By fixing the desired overtopping rate and providing a design forcing condition, the minimum required height of a seawall can be approximated using the steps detailed below.

$h_* = 1.35\frac{h_s}{H_s}\frac{2\pi h_s}{gT_p^2}$First, a non-dimensional depth, h_*, is computed as:

(1)

where g is the acceleration due to gravity. If $h_* > 0.3$, overtopping rate, *q*, is estimated as:

$$\frac{q}{\sqrt{gH_s^3}} = 0.04\exp\left(-1.8\frac{R_c}{H_s}\right) \text{ if } 0.3 < R_c/H_s < 3.5 \quad (2)$$

where R_c is the freeboard of the structure equal to $R_c = C_{el} - h_s$. For transition between $0 < R_c/H_s \leq 0.03$, a linear interpolation between the two equations is applied. Equation (2) can be rearranged to compute the required freeboard to attain the safe level of overtopping, $R_{c,eq}$:

$$R_{c,eq} = -\frac{H_s}{1.8}\ln\frac{q_{max}}{0.04\sqrt{gH_s^3}} \quad (3)$$

If $h_* < 0.2$, $R_{c,eq}$is computed as:

$$\begin{cases} R_{c,eq} = \frac{H_s}{h_*}\left(\frac{q}{2.8\cdot 10^{-4}h_*^2\sqrt{gh_s^3}}\right)^{-1/3.1} & \text{if } 0.02 \leq h_*R_c/H_s < 1 \\ R_{c,eq} = \frac{H_s}{h_*}\left(\frac{q}{3.8\cdot 10^{-4}h_*^2\sqrt{gh_s^3}}\right)^{-1/2.7} & \text{if } h_*R_c/H_s < 0.02 \end{cases} \quad (4)$$

For values of h_* between 0.2 and 0.3, the maximum of the two equations in (4) is selected as the design freeboard.

This methodology was used to compute the required freeboard height for the different habitat and sea level rise scenarios in the Placencia planning region. A reduction in the density or footprint of offshore vegetative habitats (sea grass beds) or degradation of coral reefs leads to less wave attenuation as waves approach shoreline where seawalls are proposed. Increasing sea levels also lead to larger waves at the shoreline where seawalls are proposed, keeping all other factors fixed (i.e. vegetation, offshore wave parameters) by increasing the water depth along the transects, across which the wave propagates. Sea level rise factors into the required height additionally because it increases the depth at the toe of the seawall.

The wave and erosion model was run with the same forcing as for the CZM work. Sea level rise was captured by increasing the surge elevation, an input to the Wave and Erosion Model, by the sea level rise value. The wave height at the shoreline was obtained from the Wave and Erosion model. This wave height along with the wave period and total depth (Surge+SLR) were used to compute the required freeboard under each habitat/SLR scenario. Summing the freeboard with the total depth yields the required elevation for seawall to provide safe conditions under the modeled forcing.

Model validation

The wave and erosion models in absence of vegetation have been validated by their respective authors, and have been used, for the most part, in standard engineering textbooks and guidance documents (USACE, 2002; Whitehouse 2000; Dean and Dalrymple, 2002; FEMA 2004). Although the inclusion of vegetation in the wave model has been validated by Pinsky et al. in review, we were not able to validate the erosion models because of a lack of observations.

Appendix Table 8. Description of coastal protection

OUTPUT	DESCRIPTION
Wave attenuation (m)	The reduction in wave height caused by the presence of coral reefs, mangroves and seagrass
Erosion for sandy areas (m)	Distance inland of shoreline retreat, estimated using model formulation for beaches
Erosion for muddy areas (m)	Distance inland of areas where sediment loss occurs, estimated using model formulation for muddy areas
Area of erosion (m^2)	Distance inland of erosion for muddy and sandy areas in each coastline segment multiplied by length of each segment
Avoided erosion (m)	The reduction in distance of erosion inland because of the ability of coral reefs, mangroves and seagrass to reduce waves and water level.
Land protected (m^2)	Reduction in area of land eroded because of ability of coral reefs, mangroves and seagrass to reduce waves and water level.
Avoided damages ($)	Value of property protected by coral reefs, mangroves and seagrass.

Limitations and assumptions

- The 1-D model assumes that vegetation and bathymetry features are uniform in the alongshore direction and any 2-D scattering is ignored.
- The model uses linear approximations and ignores any non-linear interactions due to phenomena such as wave-current interactions or the swaying of vegetation under wave forcing
- The retreat of the sandy be aches is computed using a heuristic model rather than computing direct erosional forcing and including complex interaction such as feedback between the waves and the eroding sea bed.
- The retreat amount of a muddy shoreline is not computed.
- Surge-induced currents are neglected in estimating the amount of sediment loss for muddy beds.

CARBON STORAGE AND SEQUESTRATION

Summary

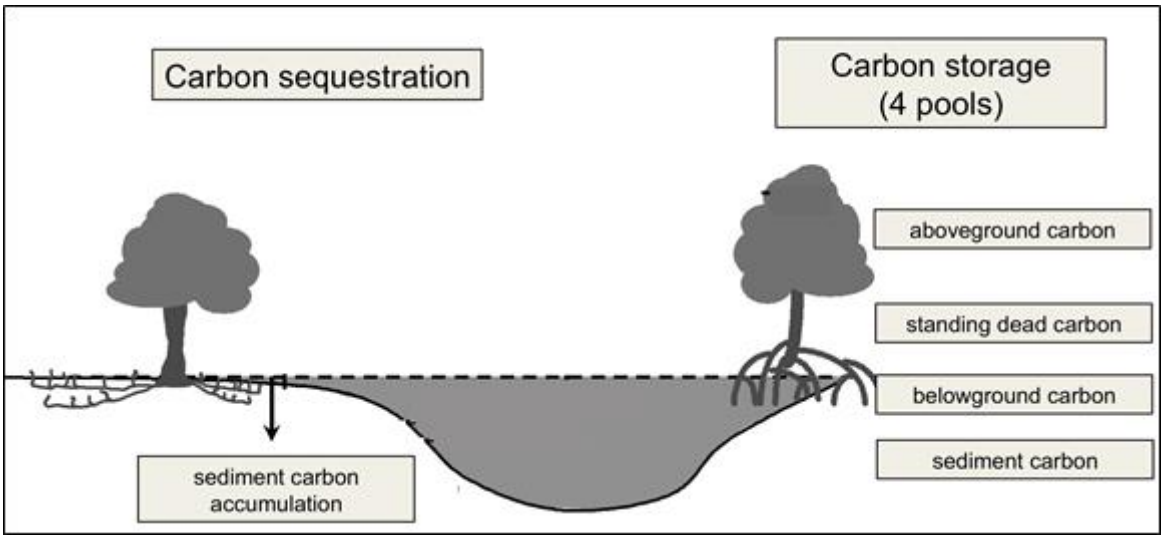
Marine and terrestrial ecosystems help regulate Earth's climate by adding and removing greenhouse gases (GHGs) such as carbon dioxide (CO2) from the atmosphere. Coastal marine plants, in particular, mangroves and seagrasses, store large amounts of carbon in their sediments, leaves and other biomass. By storing carbon, marine ecosystems keep CO2 out of the atmosphere, where it would otherwise contribute to climate change. In addition to storing carbon, marine ecosystems accumulate carbon in their sediments continually, creating large reservoirs of long-term sequestered carbon. Management strategies that change the cover of marine vegetation, such as seagrass restoration or mangrove clearing, can change carbon storage and the potential for carbon sequestration on a seascape. With estimates of the social value, or where available, market value of carbon, the InVEST Blue Carbon Model quantifies the marginal value of storage and sequestration services by comparing change in stock and accumulation of carbon between current and future scenarios. In addition to comparisons between scenarios, the InVEST Blue Carbon Model can be used to identify locations within the landscape where degradation of coastal ecosystems should be avoided in order to maintain carbon storage and sequestration services and values.

How the model works

The InVEST Blue Carbon model combines information about the distribution and abundance of coastal vegetation with habitat specific carbon stock data and accumulation rates to estimate carbon storage, sequestration and value across a landscape. The model simplifies the carbon storage and sequestration process to account for storages in four main pools (aboveground and belowground biomass, standing dead carbon and sediment carbon, see Appendix Fig 9). Accumulation of carbon occurs primarily in sediments. The model requires users to provide data layers for marine ecosystems that store carbon, such as maps of mangroves and seagrasses. The model includes a global literature review of values for carbon stocks and accumulation in the aboveground biomass and soil of various habitat types (seagrass, salt marsh, mangrove forests). Alternatively, the user has the option of including data from field studies or other sources that may be more locally specific. The model calculates sequestration based on differences in carbon stock and accumulation of carbon in sediments over time.

In Belize we assessed differences in the value of carbon storage and sequestration between the three future climate adaptation scenarios (No Action, Integrated, Reactive). We focused our analysis on carbon stored and sequestered by mangrove forests and seagrass beds. Outputs from the InVEST Habitat Risk assessment model to were used to identify differences between scenarios and across the landscape in the abundance of seagrass beds and mangroves with the capacity to store and sequester carbon. The HRA model produces maps of low, medium and high risk of mangrove and seagrass degradation for the current and three future scenarios. We compared the risk under the three future scenarios to the current, baseline scenario. Regions where risk increased to high were classified as too degraded to store and sequester carbon. Regions with an increase to medium risk had 50% of the storage capacity.

In this analysis we focused on carbon stored and sequestered by mangrove forests and seagrass beds in aboveground biomass and sediments. Because data on the amount of carbon stored at different sediment depths is very sparse, we assumed the majority of carbon is in the top meter of soil. Similarly we ignored carbon stored in below ground and standing dead biomass (Appendix Fig. 9).



Appendix Figure 7. Conceptual model of carbon sequestration and storage in marine ecosystems (Adapted from: Bouillon et al. 2008)

Using the InVEST Blue carbon model, we quantified carbon storage across the landscape by summing the carbon stored in the biomass and sediment pools and multiplying by the area of habitat The carbon stored in a grid cell *x* at time *t*, given by C_{xt} and measured in tons of CO2 equivalent, is equal to the sum of the carbon stored in each pool in the grid cell at any time *t,*

$$C_{xt} = \sum_{j=1}^{J} A_{xj}(C_{aj} + C_{bj} + (C_{sj} * d_j) + C_{lj})$$

where A_{xjt} is the area of vegetation j in grid cell *x* at time *t, d* is the depth of the sediment for habitat j, C_{aj} , C_{bj} , $C_{sj,}$ C_{lj} indicate the metric tons of carbon stored per hectare in the aboveground, belowground, soil and litter pools of habitat *j* respectively, where *j= 1, 2, ….J* indexes all the habitat types in a coastal area.

We estimate accumulation by multiplying habitat specific rates of carbon accumulation by the total area of habitat. The carbon sequestered in a grid cell *x* at time *t*, given by ΔC_{xst} and measured in tons of CO2 equivalent per year, is equal to the rate of carbon accumulation in the sediments at time *t,*

$$\Delta C_{xt} = \sum_{j=1}^{J} A_{xjt}(\Delta C_{xj})$$

where A_{xjt} is the area of vegetation j in grid cell *x* at time *t.*

Loss of carbon is a bit more nuanced since different types of human uses and/or stasis may cause varied disruption of the soils and the carbon stored below. For example, clearing mangroves for a shrimp pond may result in a high impact, while fishing or oil development may have little impact. The impact of coastal development on carbon storage varies since some types of development may involve paving over the soil and the sediment, which would still keep the storage in those pools intact. Alternatively, dredging could remove seagrasses and disturb the sediments below, releasing carbon into the atmosphere. Future version of the model will permit users to guide the model with these details as they vary across scenarios, habitats and stressors. For this application in Belize, we assumed that stressors do not disturb the carbon in the sediments. As we discuss above, the differences in aboveground biomass between scenarios were related to outputs from the HRA model. We assumed that regions where risk to mangroves and seagrass increased from low or medium to high from the current to future scenarios were classified as too degraded to store and sequester

carbon. We assumed regions with an increase from low to medium risk as a result of changes in stressors had 50% of the storage capacity.

INPUT	SOURCE	HOW THE DATA WERE USED IN THE MODEL
Seagrasses	CZMAI	Seagrasses store carbon in biomass and soils. We utilize maps showing the current distribution of seagrass beds to establish a baseline coverage of seagrass from which we estimate aboveground biomass and soils.
Mangroves	WWF	Mangroves store carbon in biomass and soils. We utilize maps showing the current distribution of mangrove forests to establish a baseline coverage of seagrass from which we estimate aboveground biomass and soils.
Carbon stock in seagrass and mangrove systems	Natural Capital Project Global Literature Reef	Carbon storage was calculated by summing the carbon stored in biomass and sediments. Carbon stocks were calculated for all of the areas of functional seagrass and mangrove in the study region. The seagrass and mangrove totals were added together to produce the total carbon in 2025 under 3 scenarios (No action, Integrated, and Reactive).
Carbon accumulation in seagrass and mangrove sediments	Natural Capital Project Global Literature Reef	Seagrasses and mangroves accumulate vast reservoirs of carbon below the sediment surface as biomass dies and gets trapped belowground. We used data on the rate of soil organic carbon accumulation rates to estimate this sequestration. We multiply accumulation rates per unit area by the total area of seagrasses and mangrove to estimate total carbon sequestration in the study region.
Social value of carbon in 2010 BZ $	USIWG 2010	The "social cost of carbon" (SCC) is an estimate of the monetized damages associated with an incremental increase in carbon emissions in a given year. It is intended to include (but is not limited to) changes in net agricultural productivity, human health, property damages from increased flood risk, and the value of ecosystem services. The social cost of carbon is useful for allowing institutions to incorporate the social benefits of reducing carbon dioxide (CO2) emissions into cost-benefit analyses of management actions that have small, or "marginal," impacts on cumulative global emissions.
Discount rate	USIWG 2010	Because carbon dioxide emissions are long-lived, subsequent damages occur over many years. We use the discount rate to adjust the stream of future damages to its present value in the year when the emissions were changed (i.e., the climate adaptation scenarios were implemented). This discount rate reflects society's preferences for short run versus long term consumption.

Value of carbon storage and sequestration

To quantify the value of carbon storage and sequestration, the Blue Carbon model focuses on changes in atmospheric carbon dioxide and other greenhouse gases as a result of changes in human activities that can affect marine ecosystems that store and sequester carbon. These changes in the atmosphere related to carbon have an effect on an array of natural systems and can result in changes in agricultural productivity, air quality, and sea level, among many other valued ecosystem services. The Blue Carbon model incorporates information about changes in the storage and sequestration capacity of the landscape with economic factors

into a single model which can estimate the value of incremental changes. The analysis we use here follows the recommendations of the United States Interagency Working Group on Social Costs of Carbon (USIWG, 2010). This report uses the latest integrated assessment models[9] to develop a methodology to inform regulatory impact analysis, and gives guidance not only on costs but also on appropriate discount rates.

In Belize we calculated the net present value of a change in atmospheric carbon that resulted from policy choices made under the Integrated and Reactive climate adaptation scenarios. To do this we calculated the specific timing of carbon flows from the Integrated and Reactive scenarios. The specific timing of flows is important as the effects of the change in carbon occur in the relevant period and have a lagged effect that reaches into the future. We accounted for this process by quoting year-specific carbon prices which reflect the discounted stream of damages from that point forward due to a change in carbon. For example, 100 tons of CO_2 released in 2050 will continue to have effects far beyond 2050, so we calculated those damages and discounted them back to 2050. Since our management decision context is the present, a proper cost benefit analysis needs to further discount those damages (at the same rate), back to the present.

Given the timing of the changes in atmospheric carbon from climate adaptation scenarios, and the schedule of carbon prices from 2010-2050 in the USIWG (2010) report, we calculated the discounted net present value of atmospheric carbon changes using a 5% discount rate. We report all results in 2010 $ BZ. With no guidance for appropriate prices for 2050-2100, we forecasted these prices using the average observed price growth from 2010-2050. Given the increasing uncertainty in price estimates through time this is a reasonable assumption which is in line with the interpolation methods for 2010-2050 used in the report.

Model validation

In the absence of detailed knowledge on the carbon dynamics in mangrove and seagrass systems typical of the Belize coast, we take the simplest accounting approach and draw on published carbon stock datasets from neighboring coastlines. We use carbon estimates from the most extensive and up-to-date published global datasets of carbon storage and accumulation rates (e.g. Fourqurean et al. 2012 and Silfeet et al. 2012).

Limitations and assumptions

- We assume the same values for carbon stored at all sediment depths.
- We assumed all storage and accumulation occurred in the aboveground biomass and sediments. We ignored increases in stock and accumulation with growth and aging of the forest.
- We assumed that carbon was stored and accumulated linearly through time between the current and future scenarios.
- We assumed that human activities that may degrade coastal ecosystems do not disturb carbon in the sediments.
- While the social cost of carbon estimates represent the state of the art in linking climatic factors to the global economy they are subject to an array of limitations and simplifications.

[9] Integrated assessment models are linked climate-economic growth models which can be used to estimated damages from the carbon emissions. Specifically the report uses data from the DICE, PAGE, and FUND models.

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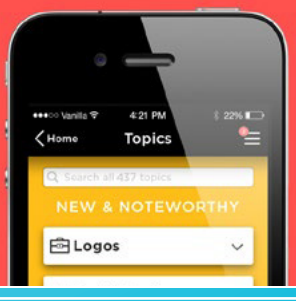
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