Embedding ecosystem services in coastal planning leads to better outcomes for people and nature

Supporting Information Appendix

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1. SI Materials and Methods

Planning Scenarios

We created planning scenarios representing alternative future arrangements of human activities within the coastal zone of Belize. These scenarios were based on a combination of information from maps of the current distribution of ocean and coastal uses, existing and pending government plans, and stakeholders' values and preferences for national and localized effects of coastal management on communities. We gathered information from stakeholders through regular meetings and presentations. Over a two-year period from 2010-2012 the Coastal Zone Management Authority and Institute (CZMAI) held 32 public meetings, advisory committee meetings, and planning workshops that included approximately 200 stakeholders. Early in the process, work with stakeholders focused on values and preferences for the future. Later consultations featured model outputs and presentations of the planning scenarios (see ref. 1 for description of stakeholder-engagement). Conceptually, the scenarios reflect three visions for the future of Belize in 2025 (see **Estimating Ecosystem Services to Inform Coastal Zone Management in Belize** in the main text**)**.

We translated the conceptual scenarios into spatially-explicit zones of coastal and marine use that CZMAI could exercise to recommend where different activities were permitted or prohibited. We synthesized and grouped data layers provided by government agencies, university researchers, and environmental organizations (Table S3) into eight broad categories of human activity (Table S1) to facilitate ease of use and enforcement in coastal areas (2). For example, commercial fishing, subsistence fishing, and recreational fishing for species such as tarpon, permit, spiny lobster, and conch were grouped into a "fishing" zone; data about snorkeling, scuba diving, and swimming were incorporated into a single "marine recreation" zone. As part of this process we developed a matrix of compatible zones (e.g. marine transportation and fishing), and zones that could not overlap (e.g. dredging and conservation). The initial result was a set of maps of the current distribution of each of the eight activities (Fig S3). This set of maps reflects spatially the current configuration of human activities in the coastal zone (i.e., the Current scenario).

Next we made changes to the current zones to visualize the outcomes from new government policies and input from stakeholders about their preferences for the future. We used spatial and quantitative data where possible. Local scientists and policy advisors reviewed changes to ensure that they were feasible futures for Belize. This resulted in a set of maps and descriptions for each of the eight zones of human uses and the conservation zone for the three future scenarios (Fig. 1, Figs. S4-S6). From a policy perspective, these maps represented alternative recommendations CZMAI could make about where to permit or prohibit activities. In our analysis, the maps represented alternative future scenarios describing the distribution of activities that could pose stress to corals, mangroves and seagrass. We used them to assess current and future risk to these ecosystems, to quantify potential change in functional habitat and to model expected ecosystem service outcomes for the Conservation, Development and several iterations of the Informed Management scenario (Fig. 4).

The Informed Management scenario evolved over time (Fig. 4, Fig. S1B). To adjust zones of human activity we first identified regions in which ecosystem service returns decreased relative to the current scenario. Next we examined changes in the area of functional habitat in this region to understand which habitats would enhance service delivery if conserved (Figs. S1B and S13A). We then worked backwards to identify which activities were posing the greatest risk

(Figs. S1B and S13B and C), and used outputs from the risk assessment to identify management options to ameliorate the risks. Points that fall in the lower right hand quadrant of an exposure vs. consequence plot are ones in which management strategies that reduce spatial overlap between activities and habitats can have the biggest impact (Fig. S13B and refs. 3, 4).

Quantifying functional habitat

To estimate spatial variation and change in ecosystem services under alternative future scenarios, we first quantified change in the distribution, abundance and other characteristics of three habitats: coral reefs, mangrove forests and seagrass beds. We began with a classic risk assessment approach (3-6) to determine which habitats and where were most at risk of degradation from the cumulative impacts of human activities in the Current and three future scenarios (4). In this approach, risk is a function of the exposure of each habitat to each human activity (spatially, temporally and given the effectiveness of management strategies) and the habitat-specific consequence of the exposure, which depends in part on life history characteristics of the species. Risk is estimated as the Euclidean distance of an activity-habitat combination on an exposure vs. consequence plot (e.g., Fig. S13B and refs. 3-6). This approach incorporates spatial data on human activities and habitats and information from the peer-reviewed and grey literature on ecological life-history and impacts of activities on habitats. Final outputs from the risk assessment step were maps of the three habitats showing where areas were at high, medium or low risk under the four planning scenarios (4).

We used the maps of high, medium and low risk (4) to estimate the area of ‘functional habitat’ capable of providing ecosystem services. We assumed that high risk areas contained 0% functional habitat. In medium risk areas, we assumed 50% of the existing habitat was capable of providing the services; in low risk areas we considered all habitat to be functional. We used these coarse assumptions for four reasons: *(i)* information about the relationship between the impact of multiple activities and ecosystem structure and function is extremely limited (7), *(ii)* they are simple and transparent, *(iii)* they were supported by CZMAI on the grounds that they wanted to follow a precautionary management approach, and *(iv)* comparisons between modeled risk to mangroves and observed data on mangrove fragmentation suggest that medium and high risk areas for the Current scenario align with regions where forests are fragmented (4). While the assumed relationships between categories of risk and area of functional habitat were appropriate for our work in Belize, they are a source of uncertainty in our analyses and a topic that deserves further research in studies aiming to ask how cumulative risk from human activities may affect flows of ecosystem services.

Next we created six sets of data layers reflecting differences in the distribution and abundance of coral reefs, mangrove forests and seagrass beds under the Current, Conservation, Development, and Informed Management scenarios, based on our assumed relationship between risk and area of functional habitat. In our analysis, habitat was recovered from current to future scenarios, in addition to preserved and lost. Some areas currently at high or medium risk shifted to medium or low risk in the future due to natural recovery once stressors were relieved. We did not model recovery through direct human intervention as restoration was not an activity under consideration in the zoning scheme.

We used the risk assessment outputs (i.e., area of each habitat at high, medium and low risk) and the total area of functional coral, mangrove and seagrass habitat in each planning region, and nationally, as metrics by which to evaluate conservation goals for the ICZM Plan

(Figs. 2-4 and refs. 1, 4). We also used maps of the functional habitat (at a 500 m resolution) as input data layers into the ecosystem service models for each planning scenario.

Summary of ecosystem service modeling

For the Current, Conservation, Development and each of the three iterations of the Informed Management scenario, we estimated the spatial production and economic value of three ecosystem services: 1) catch and revenue of spiny lobster, 2) land protected and avoided damages from storm related erosion, and 3) visitation rate of tourists and expenditures by tourists. The boundaries for the planning process and ecosystem service estimates were 3 km inland and the territorial sea (18,000 km^2, Fig. S2). We modeled services as a function of the area of habitat capable of providing the service (see 'functional habitat' above) and the distribution of human activities for each scenario. We estimated annual values in current Belize dollars for each service for the Current scenario (representing 2010 conditions) and each future scenario (year 2025) and summed these by planning region and nationally. The scale of our modeling was designed to match the scale of a national planning process that took into account regional variation**.** We projected change in each service by subtracting the model output for the year 2025 from the model output for the current scenario (year 2010). Below we summarize our approach to estimating values for the three services. More extensive details can be found in the text, tables and figures following these summaries, as well as in refs. 8-10.[1]

Spiny lobster summary. We estimated catch and revenue from the spiny lobster fishery in Belize by planning region now and under the three future management scenarios. We used an age-structured model with Beverton-Holt recruitment to model the lobster population annually from 2011-2025 (see next section **Ecosystem service modeling and data**). We modeled the population as nine regional, linked subpopulations (one per planning region, Fig. S14) connected via immigration as lobster move from mangroves and seagrass to seagrass and coral reefs. We based initial conditions on the area of functional (see above) mangrove and seagrass (habitat for larvae and juveniles), and coral reef and seagrass (habitat for adults) in each planning region (see **Ecosystem service modeling and data**). Estimates of the two stock-recruit parameters and the initial, pre-exploitation recruitment were developed by fitting three time series of catch-per-unit-effort data (model fit shown in Fig. S15). We drew other model parameters from previous studies in the region to ensure that the model best represents the Belizean population (Table S4 and refs. 11, 12). 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 converting annual lobster tail landings[2] to account for head meat, and converting from processed to whole lobster weight. Final ecosystem service outputs were harvestable catch, defined as the total pounds of the tail portion of lobster harvested, and gross revenue from landings for each planning region currently

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[1] Sharp R, et al (2015) InVEST User's Guide (The Natural Capital Project, Stanford University, University of Minnesota, The Nature Conservancy, and World Wildlife Fund); http://ncp-dev.stanford.edu/~dataportal/nightly-build/release_tip/release_tip/documentation/

[2] Ministry of Agriculture and Fisheries', 2008 Annual Report, "Agriculture, Fisheries & Cooperatives: Pillars of the Belizean Economy," Fisheries Department statistics. http://www.agriculture.gov.bz/PDF/ Annual%20Report% 202008.pdf

and in the year 2025. The current estimates compare well with reported data from the Belize fisheries department for 2010 (500,650 lbs.; $12.98 million) and 2011 (611,160 lbs.; $16.85 million). Recall that the current scenario is 2010.

Tourism summary. We estimated the spatial distribution of tourism now and under the three future scenarios by modeling the degree to which recreation in the coastal zone is a function of the locations of the marine habitats and zones of human activities that factor into peoples' decisions about where to recreate (Fig. S16). We used a simple linear regression to estimate the relationships between current visitation and human activities and habitats in 5 km grid cells. Within every cell, we computed the percent of area covered by each zone (Table S3) and functional habitat to use as predictor variables in the analysis. The response variable was the proportion of total visitor days to the coastal zone of Belize. This was approximated as the average annual person-days of photographs uploaded to the photo-sharing website flickr from 2005-2012.Photographs were found to be reliable indicators of visitation in a comparison of photo- and survey-based estimates at 836 sites, ranging in area from 80 m^2 to over 30,000 km^2, worldwide (8). Photo-user-days were regressed against the percent coverage of all attributes within each grid cell to estimate the extent to which relative visitation to a cell depends on the explanatory variables. We predicted proportion of annual person-days of recreation by tourists for the future management scenarios using the parameter values for each zone of human activity and the three habitats for the current scenario. To estimate the total number of visitor-days per cell, we multiplied the proportion computed in the previous step by estimates of total tourist-days to the coastal zone. For the Current and Informed Management scenarios, these values were estimated by the Belize Tourism Board[3]. Total tourist-days for the Conservation and Development scenarios are predictions based on the trend in visitation from 1995-2012. Tourism-related expenditures were computed by multiplying the visitation rate and the current and future expenses of tourists per day estimated by the Belize Tourism Board[4] (see next section **Ecosystem service modeling and data**).

Coastal protection summary. We estimated the area of land protected and the monetary value of these avoided damages annually for the four management scenarios. We modeled shoreline erosion and wave attenuation in the presence and absence of coral reefs, mangrove forests and seagrass beds along 1-dimensional transects perpendicular to the shoreline (Fig. S17 and refs. 9, 10). The value of erosion reduction is expressed in terms of avoided damages to property. Erosion and avoided damages are a nonlinear function of several different biological, oceanographic, physical and economic variables (10). To incorporate spatial variation in these variables, we divided the entire coast of Belize into several hundred coastline segments ranging in length from about 100 m to a little over 10km These segments differed in, for example, exposure to hurricanes, storm return period, amount of coral, mangrove and seagrass, coastal development, property values, and shoreline substrate. We then estimated reduction in cross-shore erosion for each coastline segment (see next section **Ecosystem service modeling and data** and ref. 10). We used storm surge and typical wave characteristics generated by category 1

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[3] Belize Tourism Board (2011) National Sustainable Tourism Master Plan for Belize for 2030.

[4] Belize Tourism Board unpublished data

and 2 hurricanes[5]. These two types of hurricanes have a return period of less than 15 years in Belize, thus our analysis is relevant to the 2025 time horizon of the planning process. We computed the value of coastal habitats for protection in terms of the amount of avoided land loss caused by erosion during a storm event of expected return period (Category 1 = ~ 6 years and Category 2 = ~12 years). Property values varied based on planning region and whether the land was developed or undeveloped (13).

Ecosystem service models and data

To inform the design of the Integrated Coastal Zone Management Plan for Belize we modeled three ecosystem services and produced biophysical and economic outputs for each service: 1) catch and revenue from spiny lobster, 2) land protected and avoided damages from storms, and 3) visitation and expenditures from tourism. The following text, tables and figures give more details on each of the three ecosystem service models and input data.

Spiny lobster model

Caribbean spiny lobster (*Panulirus argus*) is a heavily harvested, commercially important and widespread species found from Bermuda to Brazil. We developed a spiny lobster model for Belize to explore how ecosystem service returns from the fishery would respond to changes in lobster habitat (i.e., seagrass, mangrove, coral reef) or fishing pressure. We quantified catch and revenue in 2010 (current scenario) and for the three possible future scenarios. 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 the location where fishing for lobster occurs (Fig. 1, Fig S3-6). Using estimates of functional habitat under the current and three future scenarios (see **Materials and Methods,** the previous section on **Quantifying functional habitat** in the SI appendix and ref. 4), we quantified the area of coral, mangrove and seagrass capable of providing nursery and adult habitat in each planning region and used this as input into the lobster model. Primary model outputs are harvest of lobster tail (i.e., total pounds of the tail portion of lobster), which we refer to as 'catch', and gross export revenue generated from each harvest.

We modeled the population as nine regional, linked subpopulations (one per planning region, Figs. S2, S14) connected via immigration when lobster move from their juvenile habitat (i.e., mangroves and seagrass) to their adult habitat (i.e., seagrass and coral reefs). We modeled the population from 2011-2050 using an annual time-step, with Beverton-Holt recruitment in an age-structured model. We based initial conditions on the amounts of mangrove and seagrass (for larvae and juveniles), and seagrass and coral reef (for adults) in each planning region. Population dynamics are given by:

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[5] Organization of American States (AOS) & U.S. Agency for International Development (USAID) (1999). Storm Assessment for Belize pp 27. Retrieved from http://pdf.usaid.gov/pdf_docs/PNACK653.pdf.

$$N_{a,x,y+1} = \begin{cases} \frac{\sum_x SB_{x,y}}{SB_0}\left(\alpha + \beta\frac{\sum_x SB_{x,y}}{SB_0}\right)\frac{H_{h,x,SCEN}}{\sum_x H_{h,x,SCEN}} S_{a,x} & \text{if } a = 0 \\ \left(N_{a-1,x,y} - C_{a-1,x,y}\right)S_{a,x} & \text{if } 1 \le a \le A-1 \\ \left(N_{A-1,x,y} - C_{A-1,x,y}\right)S_{A,x} + \left(N_{A,x,y} - C_{A,x,y}\right)S_{A,x} & \text{if } a = A \end{cases} \quad \textbf{[S1]}$$

Where $N_{a,x,y}$ is the number of lobster of age *a* (*A* = maximum age = 7) in planning region *x* at the start of year *y* and $C_{a,x,y}$ is lobster catch. Spawner biomass, $SB_{x,y}$, is a function of numbers of lobster in each region, maturity, and weight at age *a* based on von Bertalanffy growth. α, β are stock-recruitment relationship parameters (Table S4 and refs. 11, 12). $S_{a,x}$ is survival from natural mortality from a-1 to a (note: $S_{0,x}$ is settlement survival from the larval pelagic stage):

$$S_{a,x} = s_a \frac{T_a \sum_{H_Z}\left(1+\frac{H_{h,x,SCEN}-H_{h,x,BL}}{H_{h,x,BL}}\right)^{d_{a,h}\gamma}}{n_h} \quad \textbf{[S2]}$$

Where $s_a$is baseline survival from a-1 to a: $s_0 = 1$, and $s_a = \exp(-M_a)$ if a>0; M_a is the natural mortality rate from *a*-1 to *a.* T_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. $H_{h,x}$ 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).* $d_{a,h}$ is the degree to which survival during the transition from a-1 to a depends upon availability of h, γ is a shape parameter, and $n_h$is the number of habitats with a $d_{a,h}$ parameter.

The harvest in numbers for each age are removed from the total biomass vulnerable to harvest as:

$$C_{a,x,y} = V_{a-1}N_{a-1,x,y-1}Ex_x; \quad \textbf{[S3]}$$

where exploitation rate is:

$$Ex_x = \frac{hc_{y=2010}}{HHB_{y=2010}}(1 + E_x). \quad \textbf{[S4]}$$

$hc_{y=2010}$ is year 2010 harvest in pounds, $HHB_{y=2010}$ is harvestable year 2010 biomass , E_x is percent change in fishing effort from baseline, and V_a 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 the proportion of harvest that is exported, the product stream (tail or head meat) and price per pound of each product stream as:

$$G_{x,y=2025} = P\frac{c_{x,y=2025}}{Z}\left(PPP_{tail}T + PPP_{head}(1-T)\right) \quad \textbf{[S5]}$$

where P is the proportion of harvest that is exported, Z is the conversion factor to scale a whole lobster to a processed one (sum of tail and head meat), $PPP_{tail\ or\ head}$ is price per pound of tail or head meat, and T is proportion of processed harvest that is tail meat (Table S4).

Appropriate estimates of the two stock-recruit parameters and the initial, pre-exploitation recruitment are critical for use of a model of this type. All three were estimated by fitting to three time series of local catch-per-unit-effort (model fit shown in Fig. S15). Data for other model parameters were taken from regional literature values to ensure that the model best represents the Belizean population (Table S4 and refs. within; refs. 11, 12). 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 (Fig. S15, Table S4) to account for head meat, and converting from processed to whole lobster weight.

The model and data include several limitations and assumptions. The population growth parameters are nationwide, not region-specific, as there were not sufficient data for estimation of region-specific parameters. Habitat dependencies are obligatory, such that lobster do not have the option to seek out acceptable substitutes, rather are constrained to depend on habitats as defined in the model. The lobster population responds to changes in the area of functional habitat, not other characteristics. The fishery is assumed to take place at the start of the year, before natural mortality, and we assumed near knife-edge selectivity in our harvest function. Harvest selectivity (and catchability) 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.

Tourism

People's decisions about where to recreate are influenced by the environment. Recreational divers prefer 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, we used the InVEST Recreation model[6] to predict the spatial distribution of person-days of recreation by tourists (8).

We explored the distribution of person-days 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 (Table S2, S3). We used a simple linear regression to estimate the degree to which each attribute relates to current visitation in the coastal zone of Belize. To begin, we divided the marine and coastal zone (3 km inland and all of the Belizean territorial sea) into 1268 hexagonal grid cells, each 5 km wide. Within every cell, we computed the percent of area covered by each attribute (Table S2, S3) to use as predictor variables in the analysis. Since we lack fine-scale empirical data on visitation to most locations, we apply a method in which current visitation is approximated by the total number of annual person-days of photographs uploaded to the photo-sharing website flickr. Photographs were found to be reliable indicators of visitation in a comparison of photo- and survey-based estimates at 836 sites, ranging in area from 80 m^2 to over 30,000 km^2, worldwide (8). Many of the photographs in flickr have been assigned to a specific latitude/longitude. We queried the flickr database for all photos taken within the Belize coastal zone from 2005-2012. Using the locations of images, along with the photographer's user

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[6] See footnote 1

name and date that the image was taken, we computed the average annual number of days that a user took at least one photograph within each cell. We then regressed photo-user-days against the percent coverage of all attributes within each grid cell (current visitation rates and attribute coverage data are log transformed) to estimate the extent to which visitation depends on all the input variables. Using these estimates, the model predicts how future changes to habitats and patterns of human use will alter visitation rates. Outputs are maps showing current and future patterns of recreational use (e.g., Fig. 2, Fig. S10).

We employed the regression coefficients (beta values) computed in the initial model run to predict future visitation, given spatial configurations of the predictors outlined in each scenario (Table S3). We used the predicted extent of functional habitat 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 and ran the model to predict visitation to each grid cell under the current and three future scenarios. 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 currently, we multiplied the proportion of person-days by 3,013,010. This value is based on the total number of incoming cruise (640,734) and overnight (277,135) visitors reported by the Belize Tourism Bureau in 2012 and the assumption that overnight visitors spend 8.56 days and cruise tourists spend 1 day in the country[7],[8] (14, 15). We also used a correction factor of 0.74 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-user-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 **[S8]**

To estimate the total number of person-days to the coastal zone for the *Informed Management* scenario, we used a similar approach. Since the configuration of human uses in the *Informed Management* 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. [S8], 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 2012-2030 there will be 6,176,769 total person-days in 2025. Thus, we calculated the total number of person-days to each cell for the *Informed Management* scenario by multiplying 6,176,769 by the proportional visitation rate per cell.

For the Conservation and Development scenarios, we estimated total person-days using a similar approach in which we assume that 4,585,196 tourists will visit Belize in the year 2025. This is based on the long-term trend in visitation from 1995-2012[9], and the value corresponds

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[7] Association for Protected Areas Management Organizations (APAMO) for Belize. Position of APAMO on the proposed cruise tourism in Placencia. http://www.nocruises.org/APAMO%20Opposition%20-%20%20long%20version.pdf

[8] See footnote 3

[9] See footnote 4

with the prediction by the National Sustainable Tourism Master Plan for 3,935,961 person-days in 2020 if the Plan is not implemented.

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, we determined expenditures 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.

The model estimates the magnitude of each predictor's effect based on it spatial correspondence with current visitation in Belize. Our approach assumes that people will respond similarly in the future to the attributes that serve as predictors in the model. In other words, people will continue to be drawn to or repelled by a given attribute to the same degree as currently. Furthermore, 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.

Coastal Protection

Understanding the role that nearshore habitats play in the protection of coastal communities is increasingly important in the face of a changing climate and growing development pressure. We used the InVEST Coastal Protection model[10] (9, 10) to quantify the protective benefits that natural habitats provide against erosion and inundation in nearshore environments.

We estimated reduction in shoreline erosion and wave attenuation provided by coral reefs, mangrove forests and seagrass beds, along a 1-Dimensional (1D) transect perpendicular to the shoreline (Fig. S17 and refs. 9, 10). We kept the physical and oceanographic data the same under all current and future scenarios and varied the extent of the three habitats based on the area of functional habitat in the Current, Conservation, Informed Management and Development scenarios. Primary outputs were land protected and avoided damages from a storm for the current and three future management scenarios.

We quantified coastal protection assuming storm surge and typical wave characteristics generated by category 1 and 2 hurricanes[11]. We chose these two types of hurricanes because they have a return period of less than 10 years in Belize (i.e., 72% chance of occurring at least once within the next decade) and are thus most relevant to the 2025 time horizon of the planning process. We estimated annual avoided damages in terms of the avoided loss of land caused by erosion during a storm event of expected return period T:

$$A_A = \frac{D_A}{T} \qquad \textbf{[S6]}$$

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[10] See footnote 1

[11] See footnote 5

where D_A is the avoided loss in property value for a given storm. The avoided loss in property value D_A is computed between two scenarios α and β as:

$$D_A = D_\alpha - D_\beta = (E_\alpha - E_\beta)V \qquad \textbf{[S7]}$$

where $E_{\alpha,\beta}$ is the area of land loss under each scenario, and V is the total property value. We estimated an average property value for each planning region based on the development status of the land (developed or undeveloped). We used property value data for developed versus undeveloped coastline from a recent World Resources Institute Report and database (13) and updated it with an online search of properties within 1 km of the coastline for sale during 2011 and 2012. The location and amount of developed versus undeveloped property differed among planning scenarios based on changes in the coastal development zone (Figs S3-S6).

We estimated loss of land during a storm for two types of coastline – sandy beach and muddy beds. For sandy beaches, we defined property loss as the erosion distance caused by the storm (i.e., 'shoreline retreat'). This assumption implies that the loss of sand is permanent after the storm. For muddy beds, on which mangroves grow, we defined property loss as a combination of the volume of cohesive sediment scoured during the storm and the distance inland from the shoreline where sediments were scoured. This assumption implies that any muddy sediment scoured during the storm is put into suspension in the water column and carried away. We describe in detail how we computed shoreline erosion for these two systems in the presence and absence of mangroves and seagrass in ref. 10. Protection from coastal erosion is a function of wave attenuation and several other hydrodynamic processes (10).

Wave attenuation due to seagrass and mangroves is a function of the density of vegetation (stems per unit area), frontal width or diameter of vegetation stems and C_d, which is a taxa-specific (e.g., eelgrass, marsh, mangroves) drag coefficient (e.g., 9, 10, 16, 17, 18). Due to the lack of site specific data, we determined the characteristics of the seagrass blades based on discussion with local experts and literature review (9, 10, 17, 18 and refs. within). We also determined the physical characteristics of the mangrove forest by assuming that the forest was composed mostly of red mangroves, based on discussion with local communities, limited site measurements by the authors and data from the literature (Table S5 and refs. 19, 20). The density of the mangrove field was linearly adjusted to take into account the patchiness of the forest and the location of the transect with respect to the longshore extent of the forest. Further, we reduced the density of shoots and roots of mangroves and seagrass in areas where these habitats were at high and medium risk from human activities under the current and three future scenarios as part of linking cumulative impacts from zones of human activities to ecosystem services (Fig. S1).

In the case of coral reefs, which have steep front and face, we computed the wave height at the offshore edge of the reef flat as a function of the offshore wave height (21). We estimated the value of the broken wave height H_r at the offshore edge of the reef top assuming that wave height is controlled by the total water depth on top of the reef h_{top}: $H_r = 0.46h_{top}$ (21). The total water depth h_{top} is the sum of the depth on the reef top, h_r, the wave setup caused by breaking waves $\overline{\eta}_r$, and any additional super-elevation of the water level caused by tides, pressure anomalies, etc. The wave setup on the reef top is of the form $\overline{\eta}_r = K_p f(H_o, T, \overline{\eta}_r, h_r)$, where H_o is the deep water wave height or the wave height at the offshore edge of the reef framework (21). The term K_p is the reef profile shape factor. It is a function of either the reef face slope α_f or the reef rim slope α_r, depending on whether waves break on the reef face or rim. Characteristics of the profiles of coral reefs are based on values in the literature (21, 22). We estimated the profile of wave height over the reef top, assuming that energy dissipation is due to bottom friction. We assumed that live coral have a friction factor of 0.2 (23).

From profiles of wave height in the lagoon, we calculated wave runup and setup and used these outputs to model shoreline retreat in sandy systems and scour in muddy systems (10, 24-27). We used the estimates of retreat and scour under different scenarios of functional habitat as metrics for calculating erosion for different segments of coastline. To compute shoreline erosion for the entire mainland, large atolls and cayes, we divided the coastline into several hundred coastal segments ranging in length from a few hundred to a few thousand meters and applied the wave attenuation and erosion models described above. The segments differed in biological, physical and economic factors that would influence coastal protection values, including extent of mangroves, corals and seagrass defending the coastline, exposure to the open ocean, and coastal development. We estimated erosion for each segment as the product of the cross-shore erosion estimated by the models and the length of the coastline segment.

The models and data include several limitations and assumptions. We assumed that all storm wave fronts are parallel to the coastline and neglected potentially important 2-dimensional wave transformation processes that can occur in some regions. While our approach is an efficient way of measuring the impact of a storm on the coastline assuming that this storm has equal probability of striking anywhere along the country's coast, it can over-estimate the impact of waves in regions of wave divergence and under-estimate the impact of waves in regions of wave divergence. We also ignored the effects of surge-induced currents which are likely to be reduced in the presence of mangroves since mangrove can reduce storm surge elevation by up to 0.4-0.5 m per km of mangrove forest (28). The errors associated with this approach have to be weighed against the relatively poor quality of the bathymetry, which in some regions had to be generated based on equilibrium beach theory, and of the topography, which had to be created based on rules of thumb presented in the literature. We assumed a constant topographic profile of 1V:600H in mangrove forests, based on estimates provided in (29). Shoreward of the coral reefs, we superimposed the surge elevation to the bathymetric and topographic profile of each transect. In regions where storm surge estimates were not available, we estimated the surge elevation using the hurricane characteristics[12] and a 1D storm surge model (30). In regions that were not directly exposed to the open ocean, such as the region in the north of the country bordering Mexico, we estimated the offshore wave height at the offshore end of those transects to be the maximum between the transmitted wave height by the coral reefs and the locally wave-generated wave by hurricane winds.

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[12] See footnote 5

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3. SI Tables

Table S1. Eleven zones of human activity included in the Integrated Coastal Zone Management Plan. The special development areas and culturally important sites are government designations that were already in place and not subject to adjustment during the ICZM planning process.

Zones of Human Activities	Description
Coastal development	Human settlements, infrastructure and economic activities to support housing, commerce, and community development.
Marine transportation	Marine area delineated for use by watercraft to transport people, goods, and cargo between multiple destinations for commuting, trade and tourism.
Dredging	Areas for the extraction of bottom sediments to maintain waterways, ports, beach re-nourishment, and minerals for the construction industry.
Fishing	Marine area for the extraction of fish for food, commercial trade, and sport fishing, in particular, wild capture of lobster, conch and finfish and catch and release of bonefish, tarpon, and permit.
Marine recreation	Marine area especially suited to swimming, snorkeling, diving, kayaking, and other water sports to support tourism, recreation, and enjoyment of aesthetic beauty.
Conservation	This zone includes coastal and marine protected areas, spawning aggregation sites, shoals, critical habitats, and biodiversity areas.
Oil exploration	Exploration for the deposits of crude oil and natural gas beneath the earth’s surface.
Aquaculture	Farm ponds for shrimp, tilapia, cobia, and associated structures.
Agriculture	Crops, orchards, ranchland and associated structures for food production and revenue.
Culturally important sites	Archaeological sites or cultural monuments, spiritual and natural heritage, aesthetic beauty, tourism revenue, recreational activities.
Special development areas	Areas with specified development activity as per the Land Utilization Act.

Table S2. Coastal and marine habitat data.

Habitat Type	**Date**	**Intended Resolution**	**Source(s)**	**Layer description / How product was made and amended**
Corals	1999	1: 30,000	Coastal Zone Management Institute of Belize (CZMI) and Peter Mumby	A dataset of shallow water (generally less than 30 m depth) coral reef locations for the Mesoamerican barrier reef from multiple sources. 30-m Landsat imagery was classified and converted to a shapefile. Includes dense patch reefs, fore reef, and reef crest. Additional coral areas in and around Glover's Reef were added after October 2011 stakeholder workshop in Belize City.
Mangroves	2010	1:100,000 or greater	CATHALAC / WWF	This dataset was developed using remote sensing of satellite imagery in collaboration between the Mesoamerican Reef program of the World Wildlife Fund and the Regional Visualization & Monitoring System (SERVIR) initiative jointly implemented by the Water Center for the Humid Tropics of Latin America and the Caribbean (CATHALAC), NASA, USAID and other partners. The goals of the dataset were to identify (i) fragmented mangrove ecosystems, (ii) mangroves at risk of fragmentation, and (iii) the resilient mangroves. Belize's national mangrove cover in 2010, based on satellite-based mapping of Belize's mangroves for 1980, 1989, 1994, 2000, 2004, and 2010, and based on the earlier work of Simon Zisman (1998). Mangrove patches on Lighthouse Caye identified by stakeholders were added to this dataset in 2013.
Seagrasses	1997/ 2007	1:110,000	Coastal Zone Management Institute of Belize (CZMI 1997) and Mesoamerican Reef Millennium study (31)	This dataset was developed in 1997 (and further refined) through the joint efforts of the Coastal Zone Management Project, the University of Exeter, the University of Newcastle and Coral Caye Conservation to delineate the various types of marine habitats located offshore Belize. A separate 2007 study was undertaken by the University of British Columbia. They conducted regional-scale seagrass habitat mapping in the Wider Caribbean Region using Landsat sensors. We combined the large expanse of seagrass along the coast in ref. 31 with the CZMI 1997 map, which did not map nearshore seagrass.

Table S3. Human activities data.

Name	**Source(s)**	**Revisions for 2010 (current) scenario**
Agricultural run-off	World Resources Institute. (WRI 2005). Belize Threat Atlas, Reefs at Risk in Belize Project. Washington DC, MA.	Digitized map: “Agricultural Runoff – Watersheds and Modeled Sediment Delivery” (http://pdf.wri.org/belize_threat_atlas.pdf)
Aquaculture	Belize Fisheries Department	Aquaculture facility locations were identified from coordinates collected by the Belize Fisheries Department (2012). The footprint of each facility was digitized using satellite imagery.
Coastal development	Jan Meerman, (BERDS 2011)	Combined BERDS digital survey on Belize settlements (www.biodiversity.bz) with additional coastal development identified using satellite imagery
Dredging	Belize Mining Department	Layer was created using point data from dredging permits issued by the mining department from 2005 to 2011.
Fishing	Belize Fisheries Department and Corozal Bay Wildlife Sanctuary Management Plan	Layer combines known fishing areas including commercial, recreational, artisanal, and sport fishing with all relevant species (SACD Socio-economic survey, 2008).
Oil exploration and drilling	Belize Ministry of Energy, Science & Technology and Public Utilities	Layer is based off the 2012 Belize Petroleum contracts map, Ocean. 2010. Offshore Drilling: Overview. *Oceana is working to oppose offshore drilling in Belizean waters.* http://oceana.org/en/ca/orr-work /offshore/drilling/overview. Accessed August 2011.
Marine recreation	Belize Tourism Board (BTB)	Layer was created from annual statistics collected by park managers and tour operators through 2011 and includes park visitation data. It maps different clusters of marine recreation activities and includes diving, snorkeling, swimming and kayaking sites.
Marine transportation	Belize Port Authority	Layer combines water taxi routes, shipping lanes and locations of port facilities through 2011.

Table S4: Description of input data for lobster model in Belize.

Input	**Source**	**How the data were used in the model**
Lobster growth parameters	Literature values (11, 12) (and unpublished M.E. de Leon González, R.G. Carrasco and R.A. Carcamo. 2008. A Cohort Analysis of Spiny Lobster from Belize) and fitting (e.g.; stock-recruit parameters fit to steepness and initial recruitment (see CPUE data below).	We used a variety of growth parameters 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.
Time series of local CPUE	Carcamo RA (2002) Report on the spiny lobster fisheries of Belize. *Second Workshop on the Management of Caribbean Spiny Lobster Fisheries in the WECAFC Area* (FAO) Fisheries Report No. 715; Long Term Atoll Monitoring Program (LAMP) fishery independent surveys at SCMR, Glover's, GSSCMR and LBCNP; WCS (2010) Glover's Reef Atoll Fisheries Catch Data Collection Program. *Glover's Reef Marine Reserve Fisheries Catch Data Collection Program Report for the period January 2005 to June 2010.* (Wildlife Conservation Society, Belize Marine Program).	The time series allowed us to estimate stock-recruit parameters and the initial, pre-exploitation recruitment (model fit shown in Fig. S15). We also used it to model the pre-2010 population.
Lobster-habitat associations	Various; based on literature values	We identified which ages are linked to which habitat types, the strength of those dependencies, and when a transition to a new habitat occurs.
Fishery operations	Legal harvest requirements (e.g., minimum harvestable size). Belize Fisheries Dept. Annual Reports (2007&2008): http://www.agriculture.gov.bz/Document_Center.html	Parameters that define fishing effort, age-specific vulnerability to and selectively of harvest were 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	We employed market operation parameters to determine the product stream that the harvested lobster enters and to express harvest as gross export revenue. Parameters included: proportion of harvest that is tail or head meat, proportion of harvest that is exported, a conversion factor between whole and processed lobster weight, and prices per pound (tail and head meat).

Table S5: Description of habitat characteristics data for coastal protection.

Habitat Type	**Diameter [cm]**	**Height [m]**	**Density [units/m^2]**	**Source**
Mangrove roots	2	0.5	90	(19, 20)
Mangrove trunks	50	3	1.2	(19, 20)
Seagrass blades	1.5	0.3	600	Refs. 9, 18 and references therein

4. SI Figures

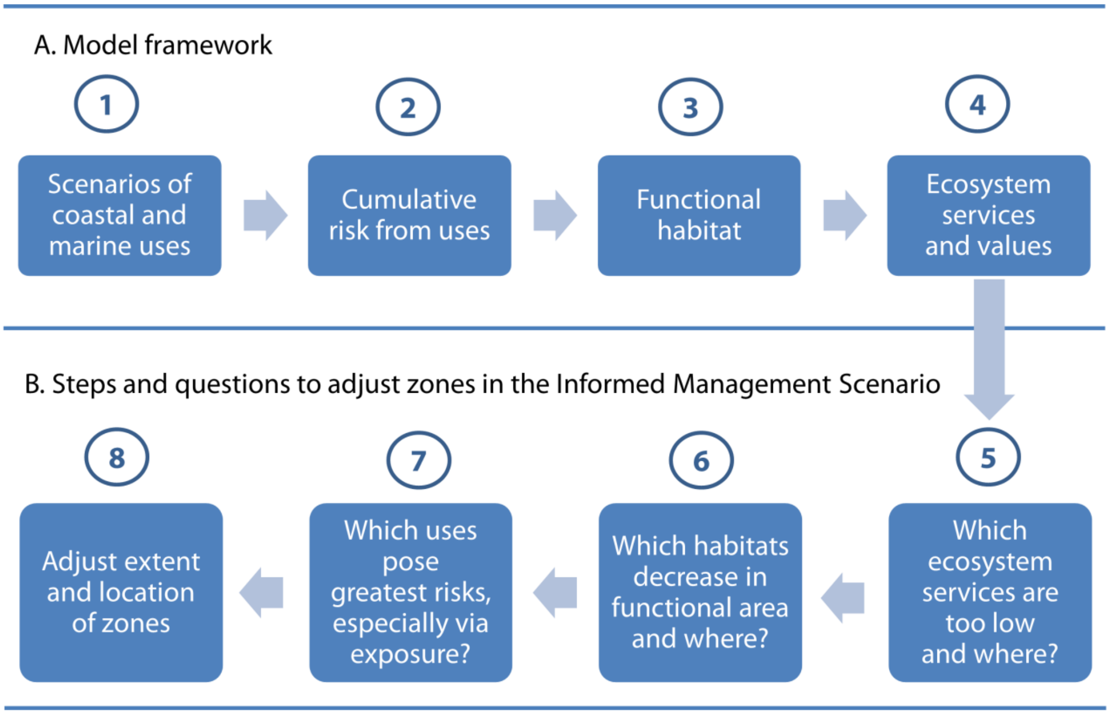

Fig. S1. *A*. Model framework for estimating risk to habitats from alternative scenarios of multiple human activities and change in ecosystem services and values. *B*. Analytical steps used to inform reconfiguration of zones for the *Informed Management* scenario. These are essentially revisiting and assessing model outputs from *A* in reverse.

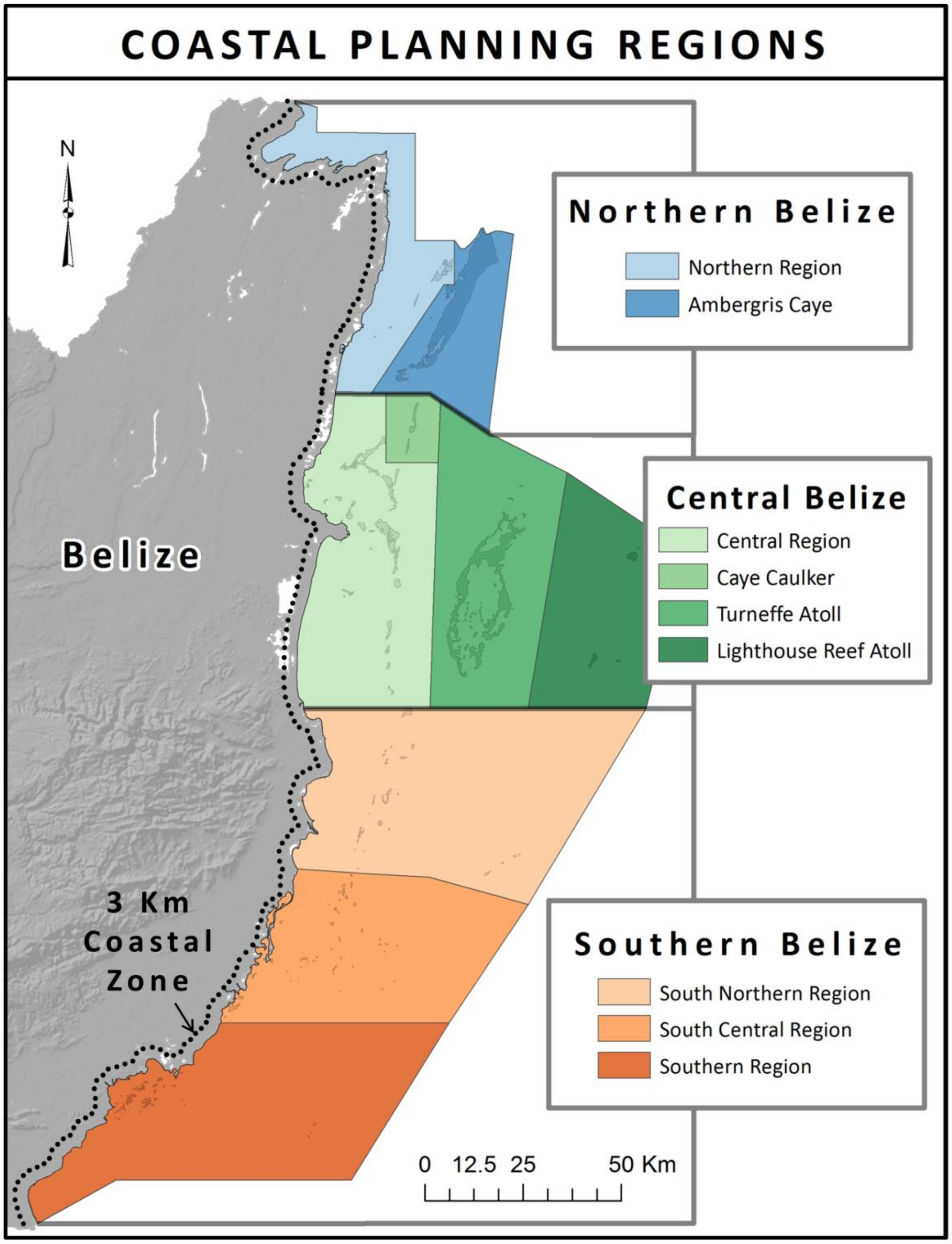

Fig. S2. The nine coastal planning regions for Belize.

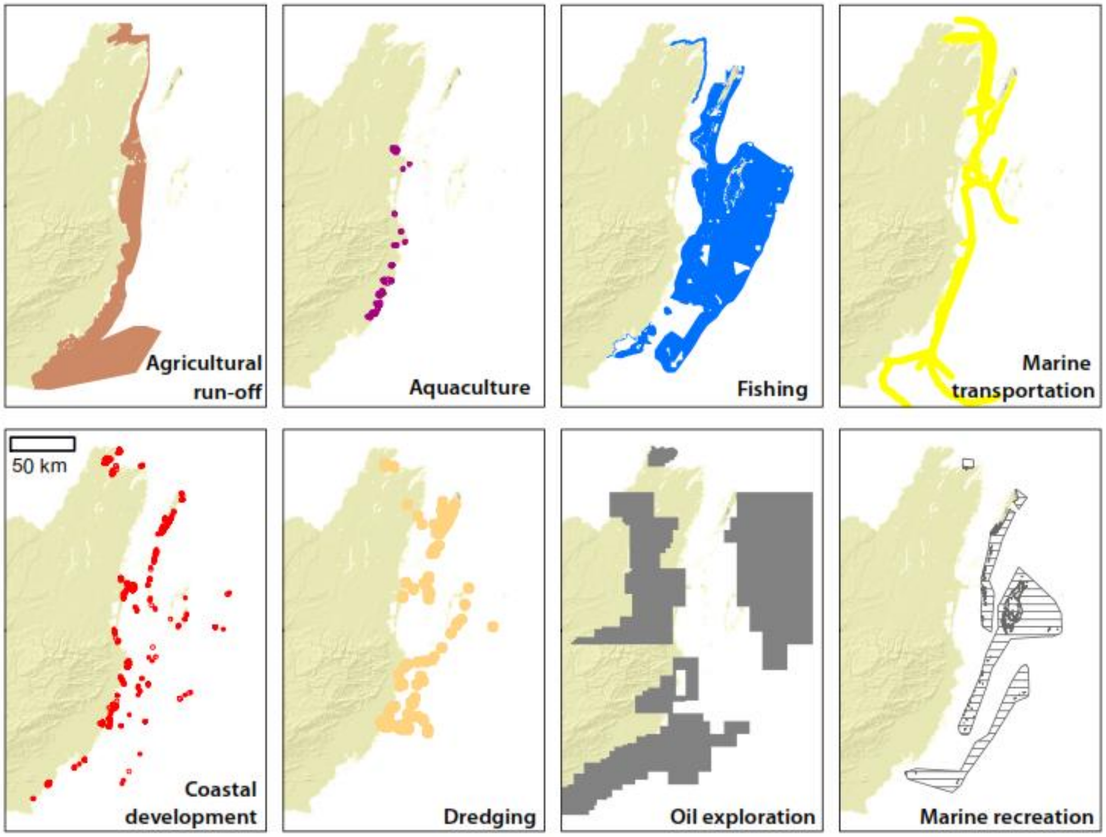

Fig. S3. Current distribution of eight zones of human activity.

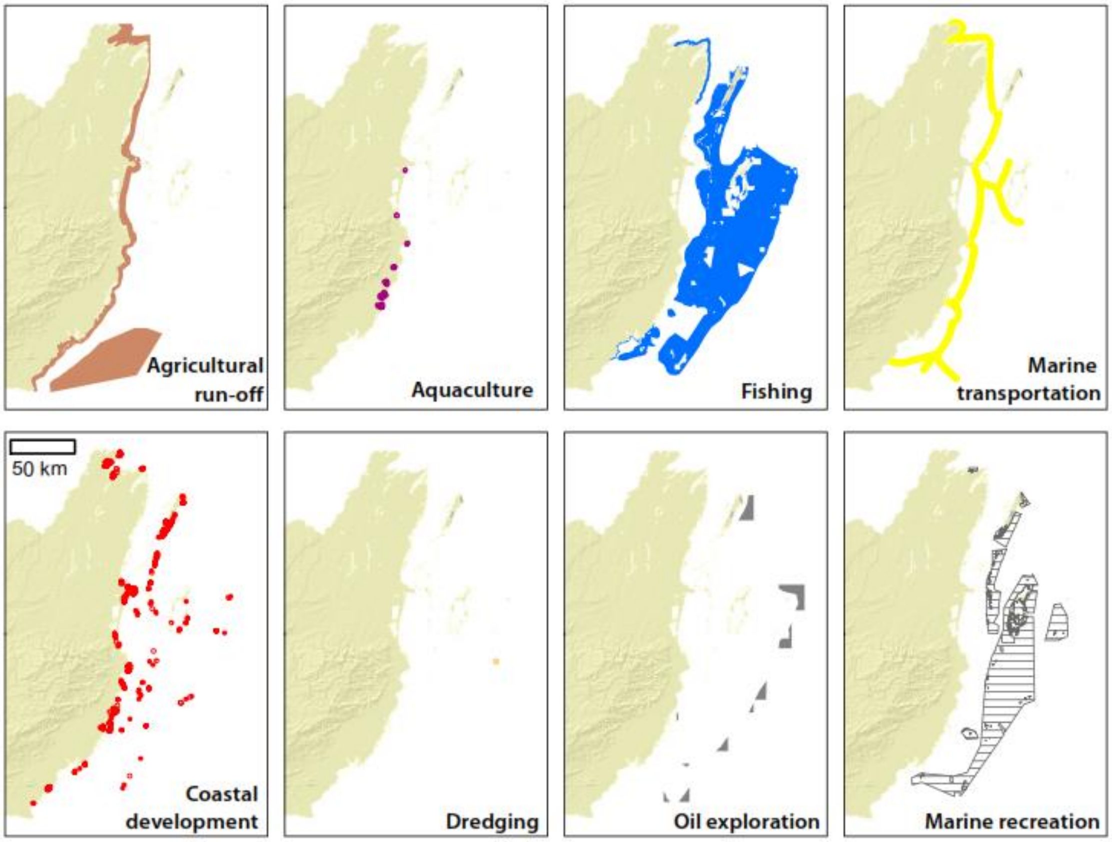

Fig. S4. Distribution of eight zones of human activity for the *Conservation* scenario.

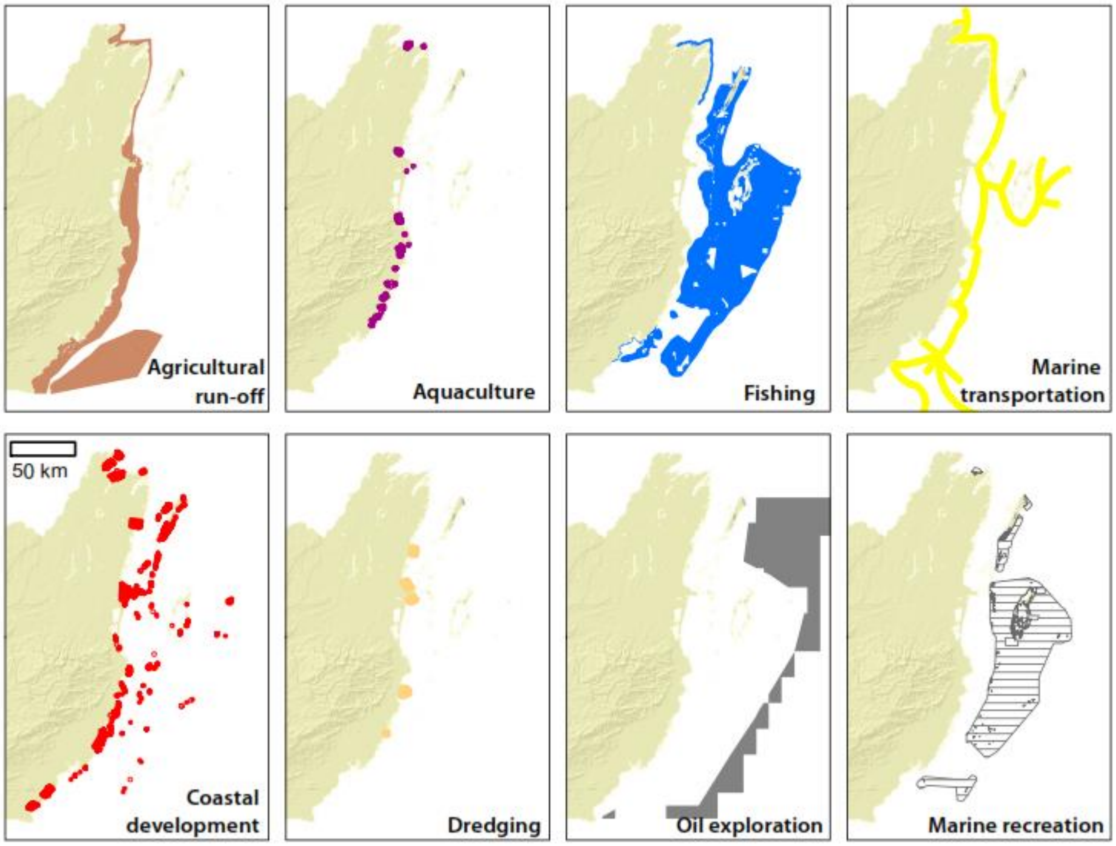

Fig. S5. Distribution of eight zones of human activity for the *Informed Management* scenario.

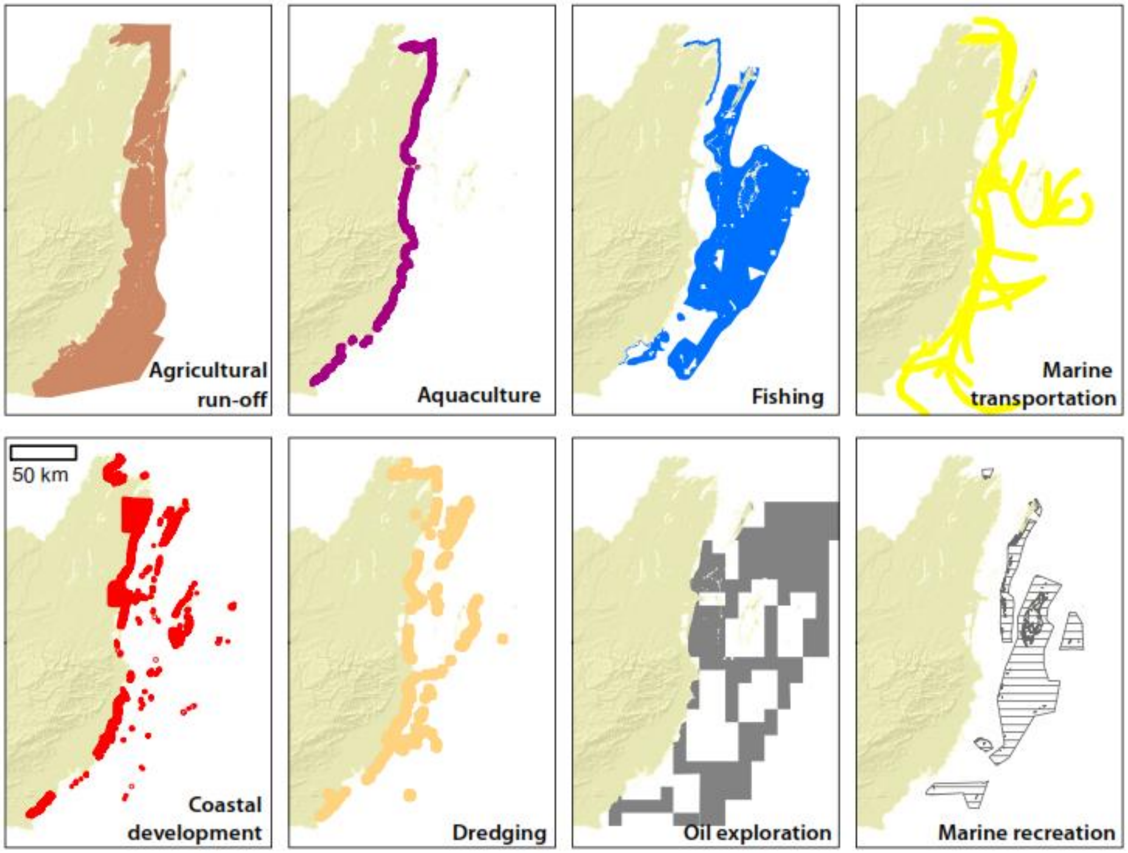

Fig. S6. Distribution of eight zones of human activity for the *Development* scenario.

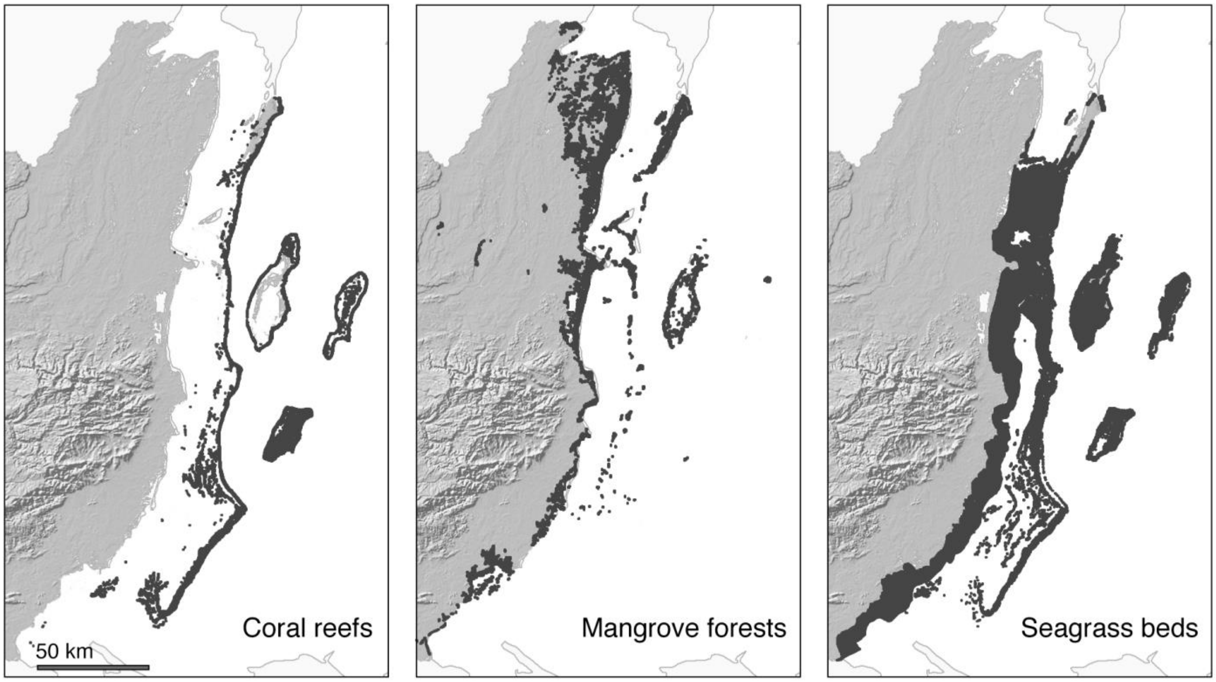

Fig. S7. Three coastal and marine habitats that contribute to ecosystem services in Belize.

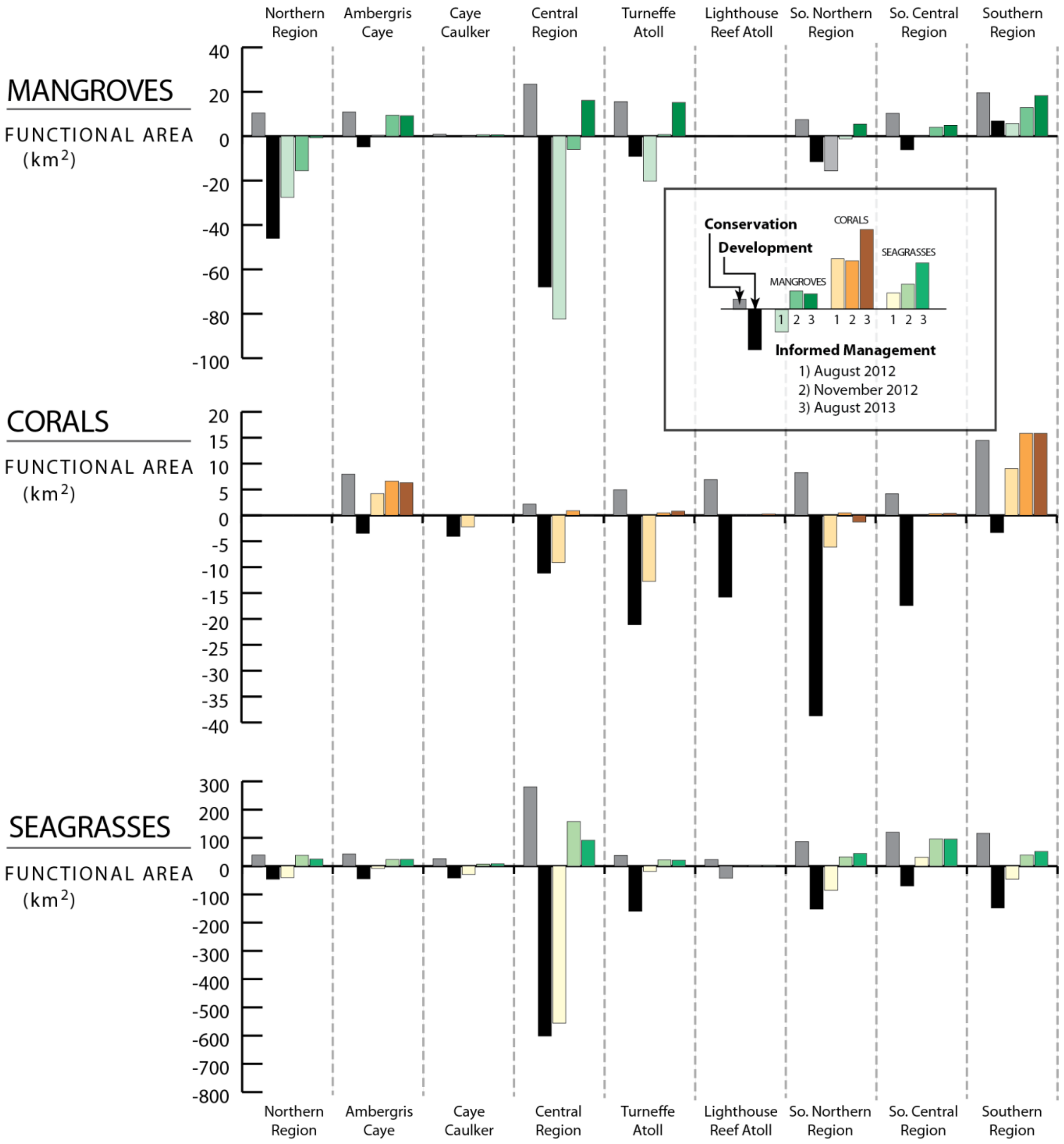

Fig. S8. Area of functional mangroves, coral and seagrasses by planning region for all future scenarios relative to the *Current* scenario.

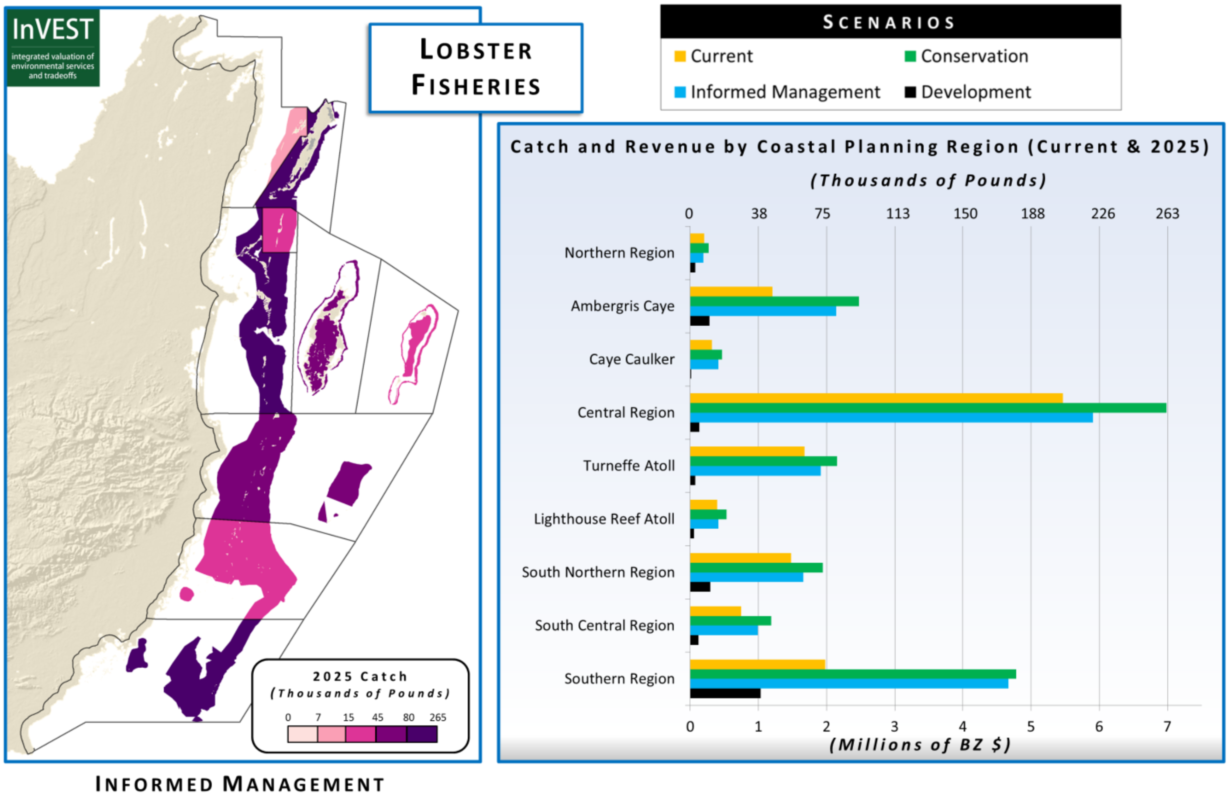

Fig. S9. Spiny lobster catch for the Informed Management scenario (2025). Bar graphs (right) show variation by planning region in lobster catch and revenue across the current and three future scenarios.

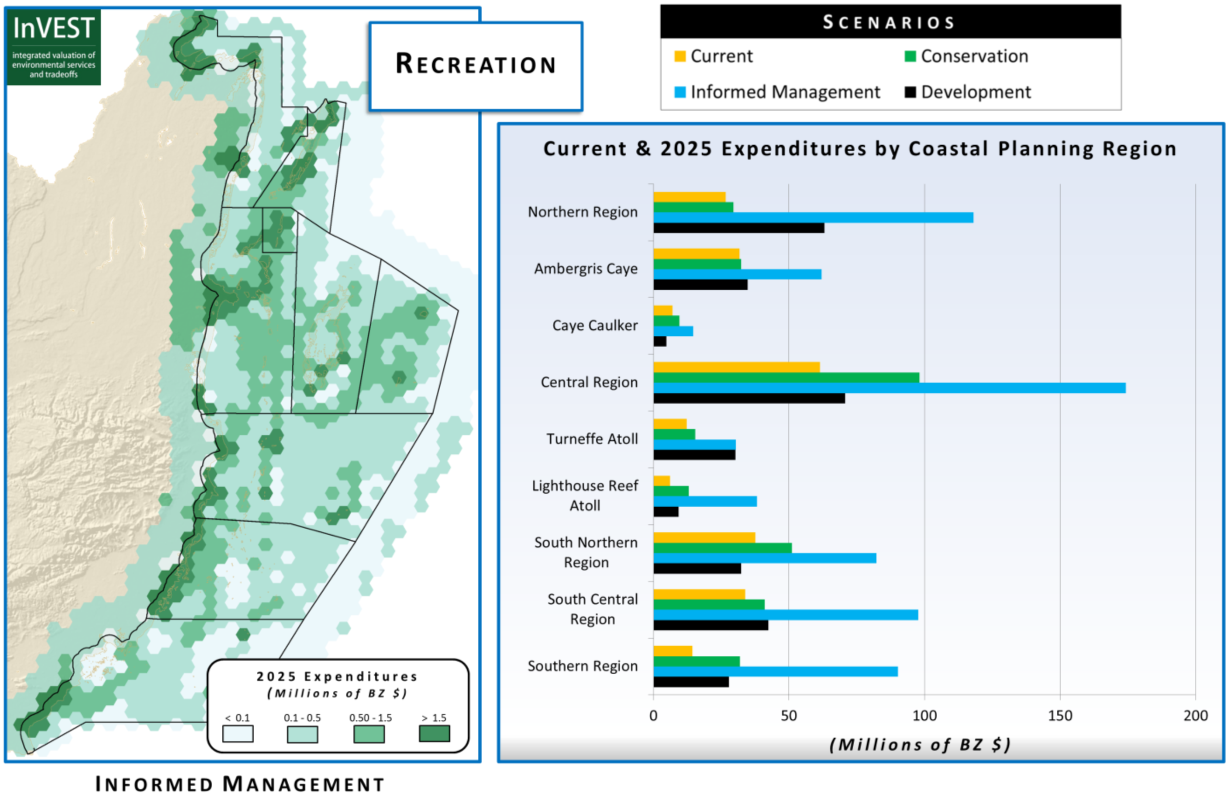

Fig. S10. Tourism and recreation expenditures for the Informed Management scenario (2025). Bar graphs (right) show variation by planning region in expenditures across the current and three future scenarios.

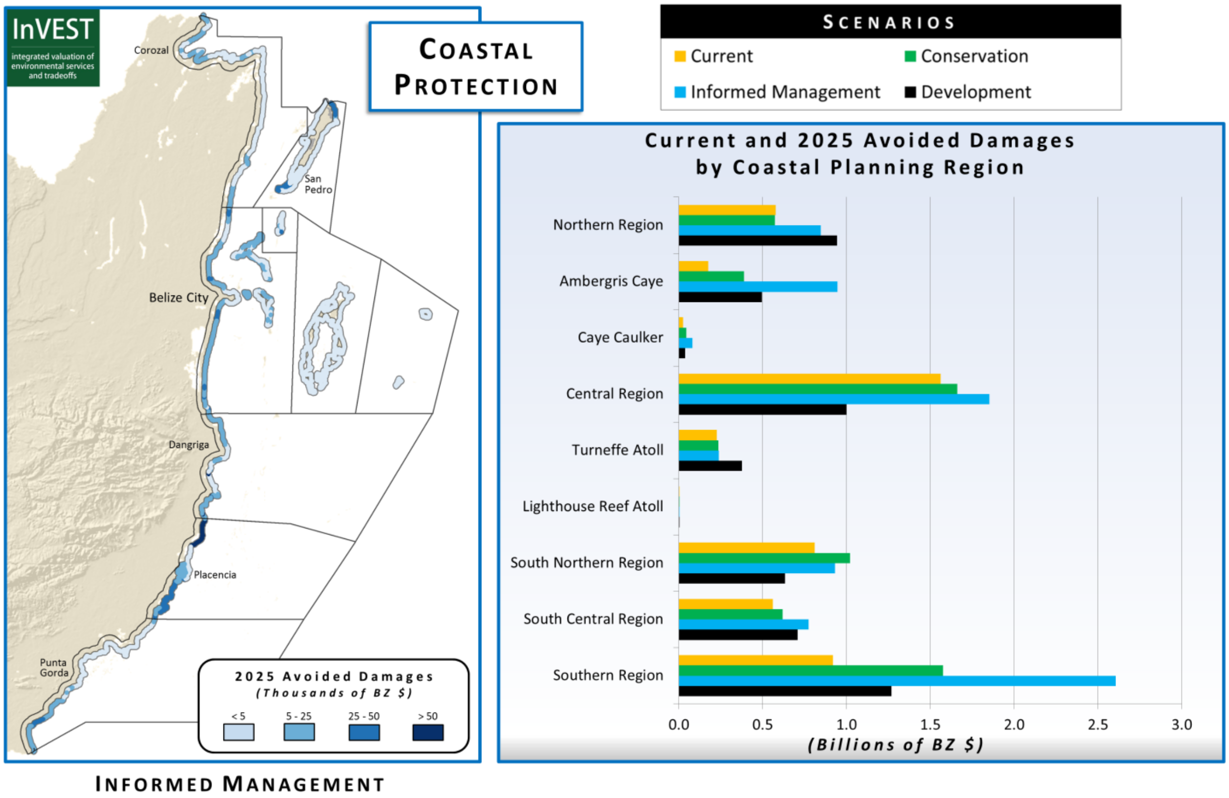

Fig. S11. Annual avoided damages for the Informed Management scenario (2025). Bar graphs (right) show variation by planning region in avoided damages across the current and three future scenarios.

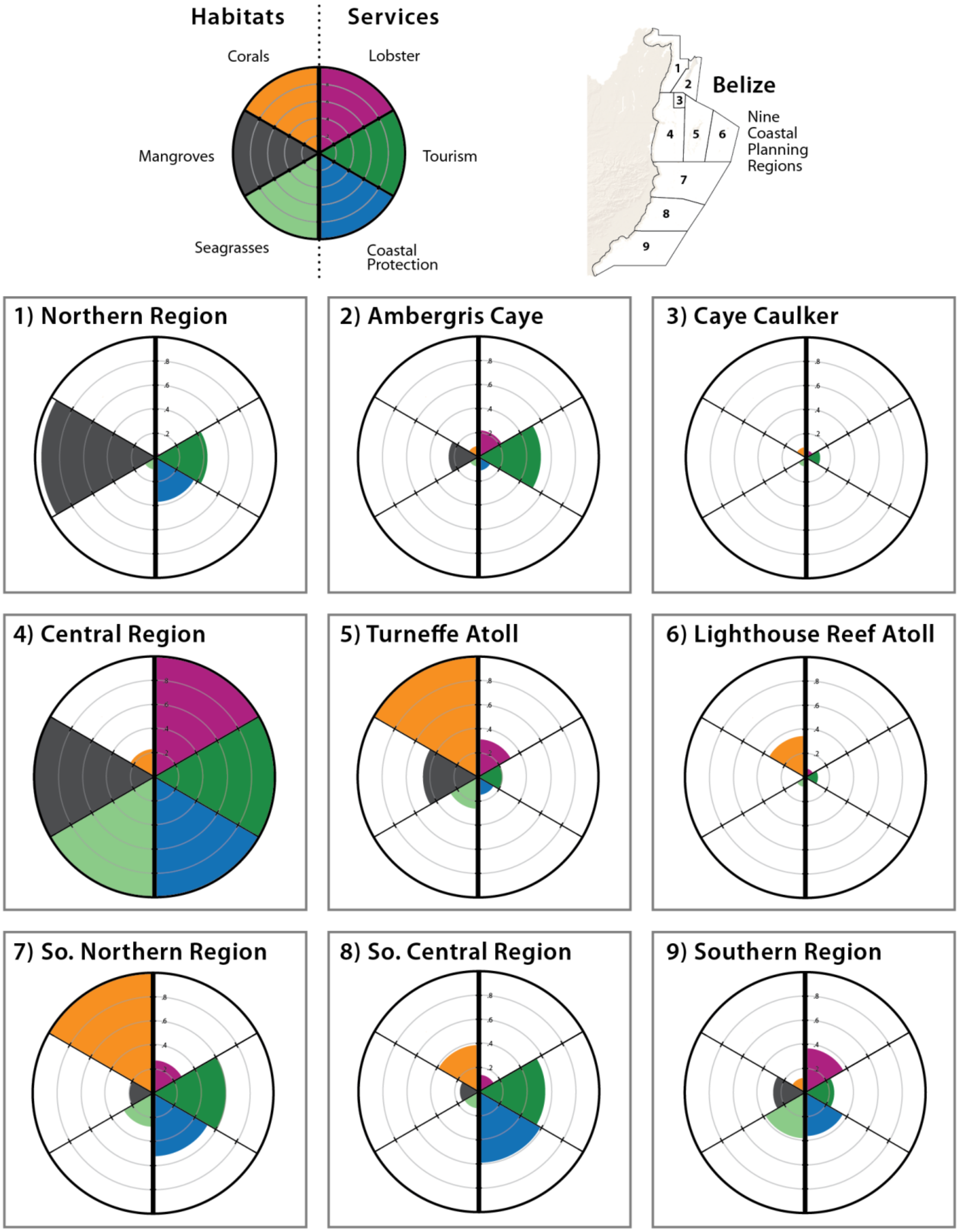

Fig. S12. Relative contribution from nine planning regions for the *Current* scenario in terms of area of functional habitat (left side) and three ecosystem services (right side).

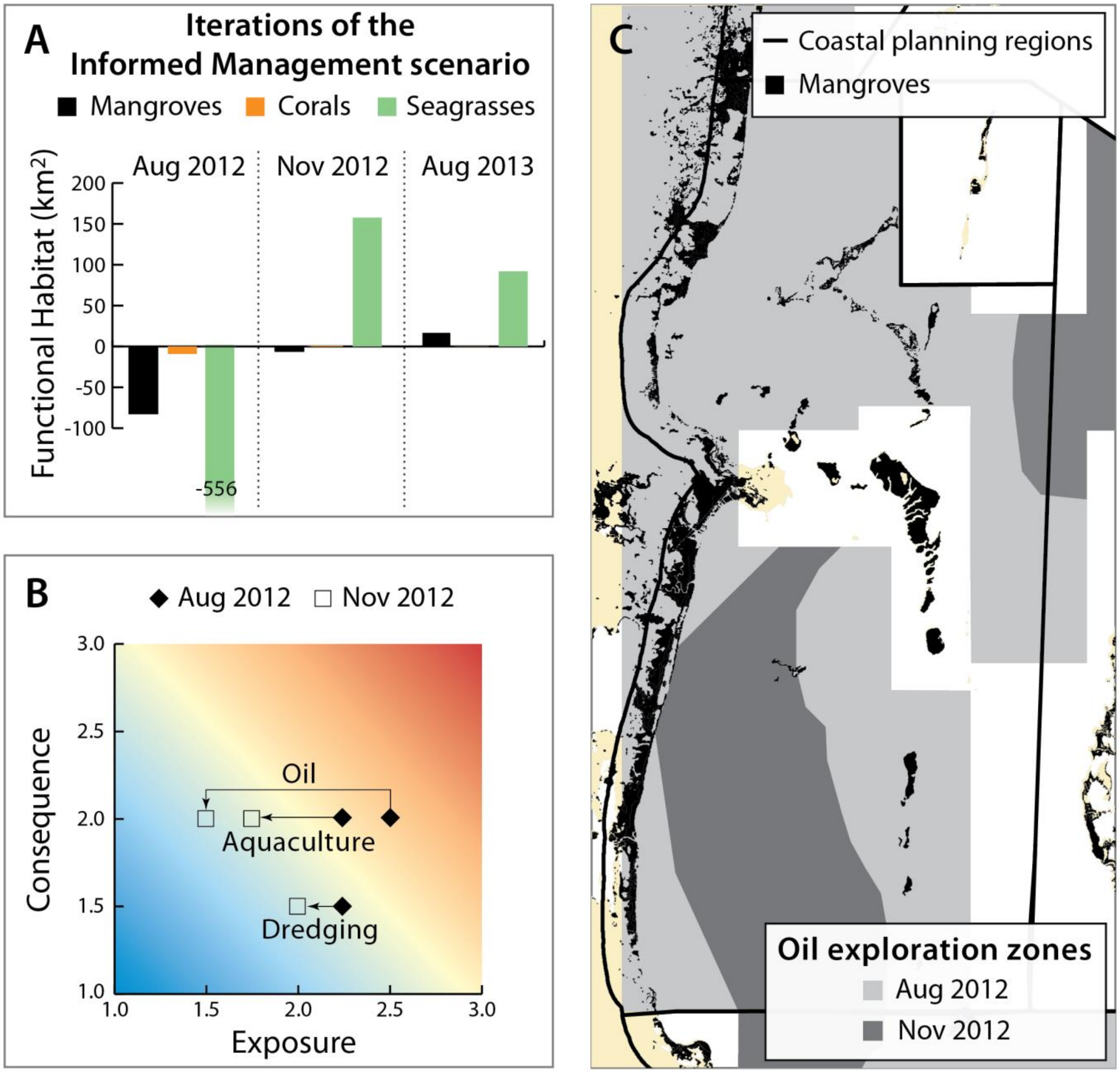

Fig. S13. Analytical components underpinning changes in zones of human activities using the Central Planning Region as an example. A) Difference in area of functional habitat in three iterations of the Informed Management scenario relative to the Current scenario in the Central Region. B) Risk assessment plot showing shift in exposure of mangroves in the Central Region to three human activities (**Materials and Methods** and ref. 4). For simplicity we show only those activities that overlapped less with mangroves in the Central Region in November 2012 than in August 2012 as a result of changing the extent and location of these zones. C) Oil exploration zone in the Central Region for the first two iterations of the Informed Management scenario. In the final version of the plan this zone does not overlap the Central Region -- a result of the oil drilling referendum in Belize during the time of this planning process.

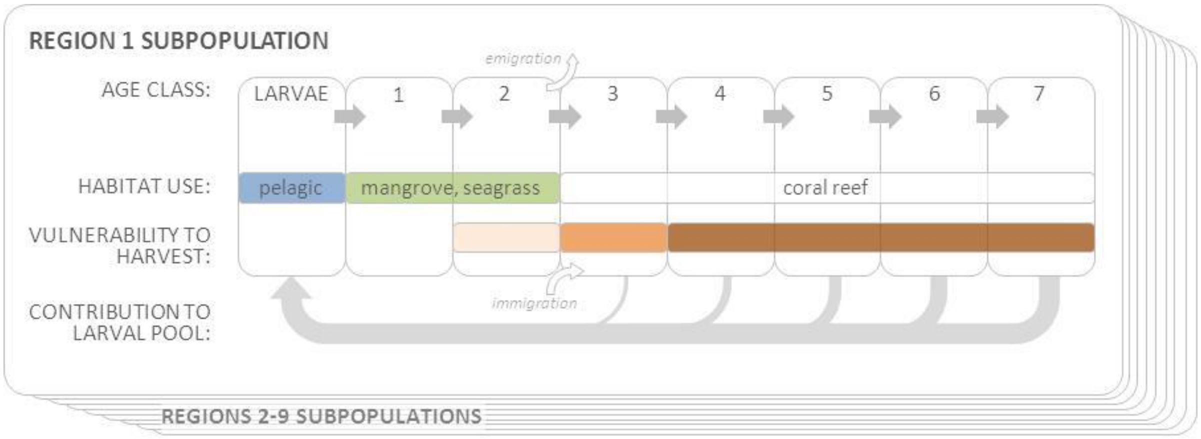

Fig. S14. Conceptual diagram of lobster model where each subpopulation aligns with a coastal planning region.

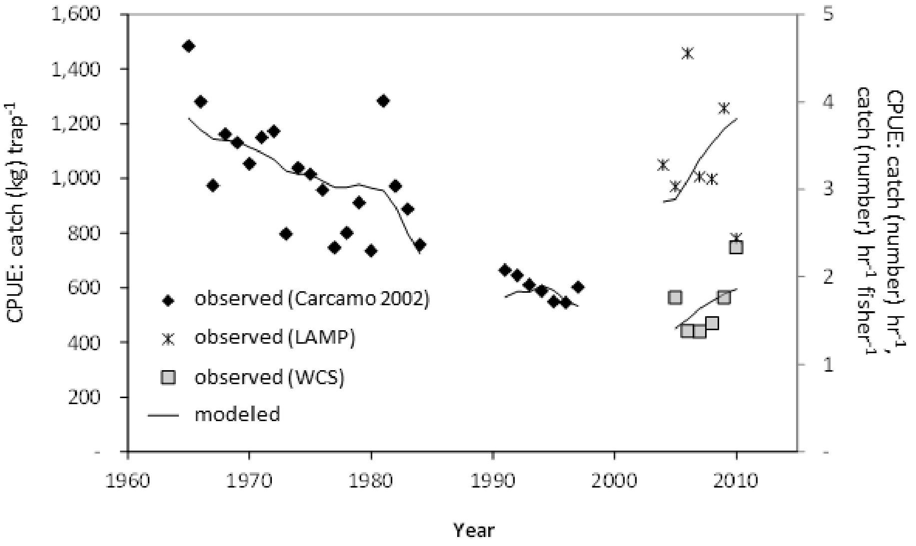

Fig. S15. Model fit to three time series of catch-per-unit-effort (CPUE). Left y-axis catch trap^{-1} data are from Carcamo 2002. Right axis catch hr^{-1} are from LAMP. Right axis catch hr^{-1} fisher^{-1} are from WCS (see Table S4 for full description of data sources).

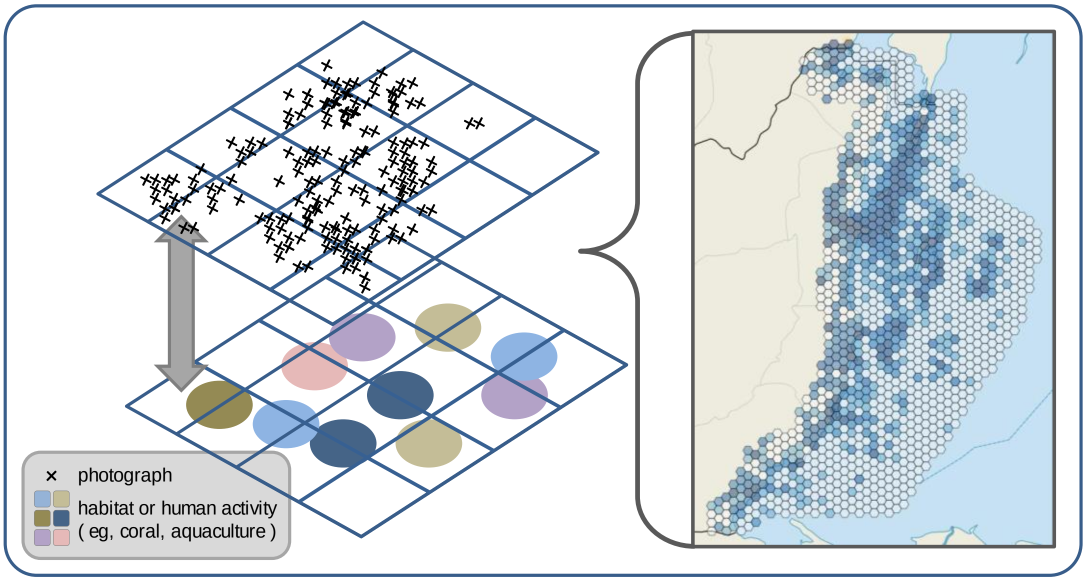

Fig. S16. The model uses the relationships between locations of geo-tagged photographs and coverage of natural habitats and human activities to predict where in Belize tourists will visit. Darker polygons indicate more visitors.

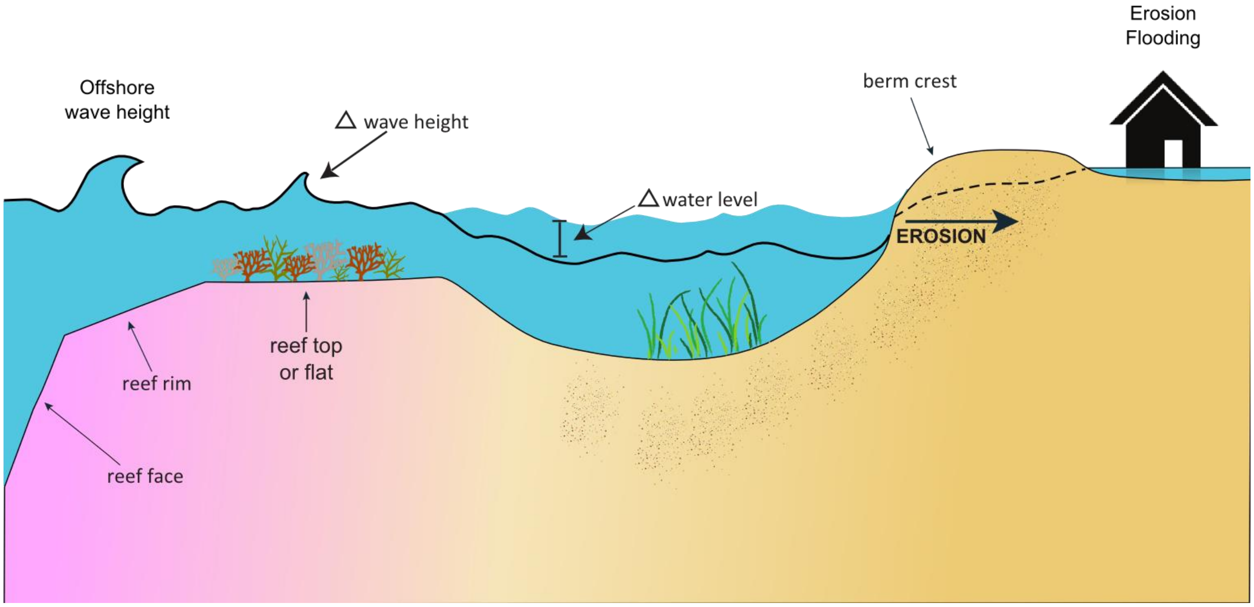

Fig. S17. Coastal protection conceptual model (adapted from ref. 10). Reduction in erosion and avoided damages provided by mangrove forests was included in the analysis of muddy segments of coastline (not pictured here).