A VISION FOR PROTECTING MARINE RESOURCES ACROSS THE CARIBBEAN BIOLOGICAL CORRIDOR

TECHNICAL REPORT
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TECHNICAL REPORT
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I. Introduction

Tropical marine ecosystems are inextricably linked, sharing strong connections that pay no attention to political boundaries. The strong and predictable ocean current in the Caribbean, meanders through the basin year round transporting larvae between islands and regions. Large ranging and highly migratory species such as turtles, whales, sea birds and pelagic fishes inhabit different portions of the Caribbean Basin during different stages of their life cycle. Despite this high degree of mixing, there are significant differences in geology, climate, productivity, and island size, all of which influence the relative abundance, extent, intactness, and vulnerability of marine biodiversity in the Caribbean. The spatial differences that exist characterize three distinct ecosystems within the Insular Caribbean: The Bahamian, The Greater Antilles and The Lesser Antilles (Figure 1).

The island nations of the Greater Antilles, or the Central Caribbean, which encompass Haiti, the Dominican Republic and Cuba, share many marine species and experience the same environmental threats that are found elsewhere in the Caribbean. Each country in the tri-national corridor has developed a different response to these challenges. Cuba has a fairly well-managed Marine Protected Area (MPA) system with no-take zones; the Dominican Republic has several MPAs that habitually suffer from lack of resources and poor management, while Haiti is void of any MPAs legislation (Figure 2). Between the three islands, there exist 188 declared terrestrial and marine protected areas with marine areas totaling approximately 1.1M hectares (Guarderas et al., 2008). However, these areas are largely "paper parks," meaning that although formally declared, they lack protected area plans and the funding necessary to implement park management objectives.

Similar to other tropical regions in the world, the Caribbean's lack of marine protection and management puts each nation's marine and coastal resources at risk. According to the World Resources Institute's Reefs at Risk Analysis, 70 percent of Cuba's reefs are threatened, with over 35 percent at high risk; while 80 percent of the DR's reefs and 90 percent of Haiti's reefs are at risk due to increased sedimentation and pollution of coastal zones brought on by swelling coastal populations, uncontrolled development and tourism, over-fishing, extensive land-clearing and poor agricultural practices (Burke and Maidens, 2004). To make matters worse, there are no trans-boundary management plans or shared threat abatement strategies between the countries.

Figure 1. The Insular Caribbean is home to three distinct marine ecoregions.

Figure 2. Map of terrestrial and marine protected areas across the Central Caribbean.

With less than seven percent of all Caribbean islands and waters protected and a small percentage of those areas actively managed, the coral reefs, beaches, rivers, forests and fisheries that are the foundation of all life in the Caribbean are increasingly at risk. Changes in these ecosystems are being magnified by already depleted fish stocks and degraded coral reefs; saltwater intrusions into freshwater resources, which end up in forests and croplands thereby diminishing crop yields and food production; and by the increase in diseases and infrastructure damage caused by extreme tropical storms, flooding, drought, and higher temperatures. It is expected that climate change, over the next 20-50 years, will bring more intense hurricanes, flooding, sea-level rise and coral bleaching. These changes will have predominantly adverse and often irreversible impacts on

Caribbean coastal ecosystems and their services, causing significant negative social, cultural and economic consequences

While solutions to these problems can be addressed at a national scale, we believe the long-term effectiveness of national-level measures will be compromised in the absence of a corridor-wide approach, where multiple countries discuss and resolve problems together. This project has provided an much needed opportunity to work with a delegation committee to develop a tri-national marine action plan for the Caribbean Biological Corridor. These countries share an interconnected marine environment and the impacts of the environmental risks previously mentioned are being felt throughout the region (Grober-Dunsmore and Keller, 2008).

The development of a tri-national peer network provides a platform to identify common issues, coordinate problem solving, and share and effectively allocate and distribute resources. The use of geographic information systems (GIS) has been a core technology upon which models have been produced, which are providing insight and discussion topics for developing conservation strategies for shared marine resource issues that address both environmental and economic conditions. Consistent with the MacArthur Foundation's objectives, *the development of a marine action plan has provided the opportunity to share science and best management practices, foster coordinated action, and assist with the building of local capacity to address the impacts of climate change while abating threats to marine landscapes*. TNC will continue to work with members from the Caribbean Biological Corridor steering committee and marine experts from the region to implement the conservation action planning steps identified in this report, helping to guide the countries toward an agreement on shared conservation targets, threats and management strategies.

II. Project Overview

The primary goal of this project was to set in motion a tri-state marine action plan that identifies common problems across the region, consolidating information, and gathering stakeholder input for responding to marine biodiversity loss and climate change adaptation needs from a marine corridor perspective. Marxan, a systematic site selection software used around the world for designing protected area networks, provided regional decision support for identifying the most important marine areas to protect (Ball et al., 2009). The Marine Action Plan provides a road map for identifying the highest priority marine issues between the three countries using the latest data and information on biodiversity importance and human activity pressures, forming a framework for decision-making centered on resource allocation. Specifically, the deliverables for the Marine Action Plan for the Caribbean Biological Corridor include:

- A seamless and consolidated GIS database of marine conservation targets, regional threats layers, and up-to-date marine protected areas that have been validated by in-country experts.

- The identification of gaps in marine protection based on the current MPA network as well as a portfolio of important marine areas to protect from a regional perspective that meet conservation goals and consider underlying threats.
- The identification of important marine conservation corridor areas, showing how countries throughout the Caribbean depend on one another based on modeled larvae dispersion, settlement, and recruitment.
- Results from a multi-country stakeholder workshop that identified and agreed on region-wide protection and management strategies and next steps for strategy implementation.
- Inclusion of all data and model results into the TNC's Conservation Information System for public dissemination and to support regional conservation actions throughout the Caribbean.

Caribbean Biological Corridor Workshops

As part of the technical component of the workshop, Dr. Steve Schill presented a summary of the work accomplished to date, specifically on Caribbean-wide coastal and marine target ecological assessments, sources of data and associated data limitations, and recommendations for data refinement and enhancement. His presentation included an overview of methods that were used to create and assemble the marine and coastal habitat-level targets (taking advantage of recent access to high resolution satellite imagery streamed over the internet directly through Desktop GIS software) and the online database Ocean Biogeographic Information System (OBIS) that was used as a resource for marine and coastal species-level targets. An overview of the methods used to develop the Caribbean-wide marine threat model also presented. The second part of the technical presentation addressed principals of ocean connectivity and how marine scientists are using satellite data and GIS technology to model and better understand ocean connectivity patterns and larvae transport. Draft results of the first round Caribbean marine connectivity larvae transport model were presented for review and copies of all target, threat, and model information were given to workshop participants with a request to provide edits and suggestions to be incorporated in future model runs. The workshop ended with a discussion on the proposed methods of how to incorporate all three deliverables (revised marine conservation targets; marine threat model, and connectivity patterns) into a Marxan decision-support framework. Designing a marine protected area network within such a framework, provides an efficient way to meet conservation goals, consider threat impacts, and takes advantage of identified marine corridors. Details of the technical methods used are described in the next sections.

Consolidation and Refinement of Marine Conservation Targets

Biodiversity features used in a protected area design are often termed *conservation targets* and are the basis for setting goals that focus conservation planning and action. The consolidation and refinement of mapped marine and coastal conservation targets was one of the key outputs created for the Marine Action Plan. These targets are critical input for Marxan which are used to identify high priority areas of overlapping marine biodiversity while considering the underlying threat models that may impede conservation success. Such areas contain multiple and viable or feasibly restorable examples of marine species, ecological communities, and systems across key environmental gradients. The geographic location and spatial context of these marine conservation targets and associated goals are required to run Marxan, which seeks to identify an optimal suite of protected areas that meet conservation goals in an efficient way (minimum threats).

Recent access to online streaming of archived high-resolution satellite image libraries within GIS software, permit scientists to review, update, and consolidate spatial information in a way never before possible. Consequently, all Caribbean marine and coastal conservation targets created for this project were refined in a way not previously possible at such a broad scale. Previous attempts to map features at high levels of accuracy for large area like the Caribbean Basin, were cost-prohibitive and often relied on the use of coarser and more affordable satellite image datasets (e.g. Landsat). The baseline marine target features that were refined came from TNC's Conservation Information System – a compilation of the most accurate sources of environmental and socio-economic GIS data created from 2004-2006 for the Caribbean Ecoregional Assessment (Huggins et al., 2007). These baseline data were refined to much higher-level accuracy requirements (e.g. 1:100,000 to 1:12,000) using detailed and manual heads-up digitization techniques. This was done using the archived orthoimage database servers that streams scenes from IKONOS, Quickbird, and other high resolution (1.0 x1.0 m) satellites over the internet and into GIS software for image interpretation and digitization. Figure 3 shows examples of marine targets that were digitized from high resolution satellite imagery for the area of Jaragua National Park, Dominican Republic. Each marine conservation target was captured as a separate feature dataset within the GIS database, projected to the Web Mercator projection, and accompanied with TNC-compliant metadata. For areas of data void, where the terrain was not visible due to cloud cover in the orthoimage database, we interpreted Google Earth imagery to create Keyhole Markup Language (KML) files, which were then exported to an ESRI Shapefile format and uploaded to the GIS database in TNC's Conservation Information System.

Species-level targets were also assembled using the Ocean Biogeographic Information System (OBIS), an online repository of species level data that was established as a project of the Census of Marine Life to help facilitate global enfranchisement of data within the scientific community. Over 300,000 species records were downloaded and compiled into the GIS database. A map showing the distribution of species occurrences can be found in Appendix B. However, upon reviewing these data, it was decided that they were unsuitable to use in Marxan, since suitable input targets should be consistent and evenly distributed throughout the study area in order to avoid bias in model outputs. However, these species records have been included in TNC's Conservation Information System and were distributed to workshop participants for future use. A listing of all marine conservation targets, their individual Marxan IDs, and corresponding total hectares or kilometers (for linear features such as rocky shores) are listed in Table 1.

All marine habitat and species targets were presented at mid-project stakeholder review workshops and countries received copies of these data so they could edit and refine these data through in-country expertise. Once target edits were received back, they were then used as updated inputs in the marine connectivity and Marxan analysis. Descriptions of all marine targets used in this project, including detailed mapping methods are found in Appendix A. Maps for all targets, threats, and model results can be found in Appendix B. Table 2 lists the suggested edits to marine targets that were collected at the October workshop and the associated response and/or resolutions that were taken.

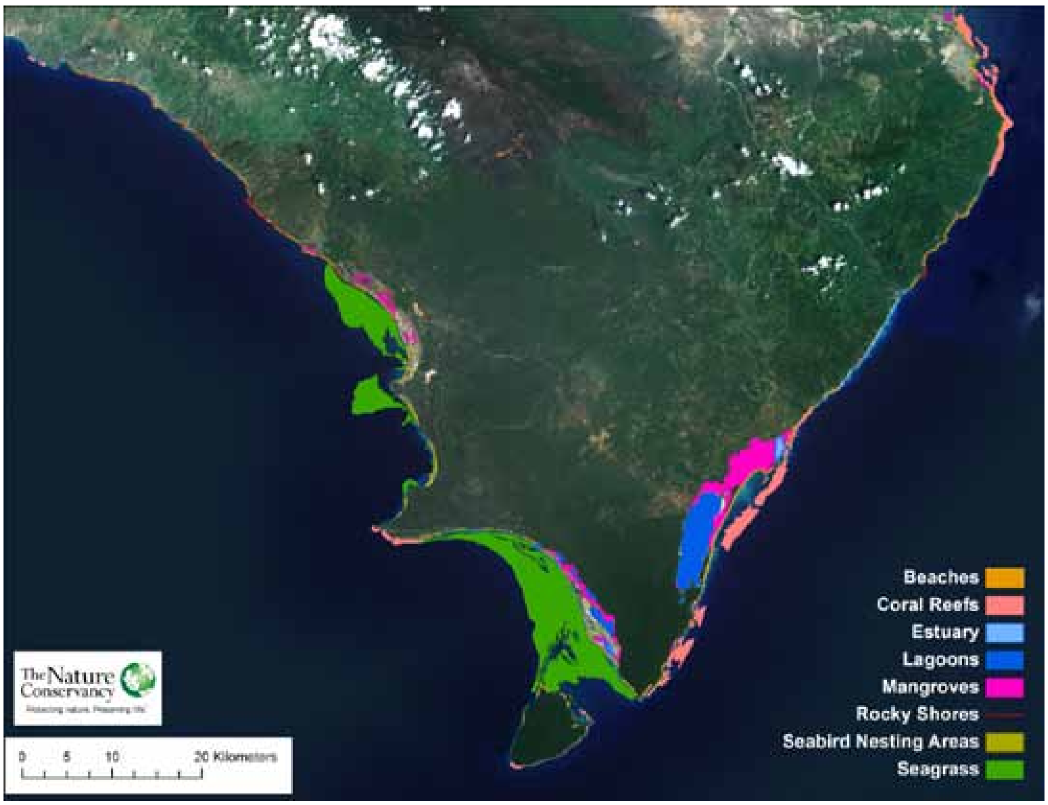


Figure 3. Examples of marine targets that were digitized from high resolution satellite imagery for the area of Jaragua National Park, Dominican Republic.

Table 1. Marine Conservation Targets used in the Insular Caribbean Marxan Analysis

MARINE CONSERVATION TARGET	ID	Hectares
Bahamian Coral Reef	1012	291,067
Eastern Caribbean Coral Reef	2012	92,014
Greater Antilles Coral Reef	3012	462,129
Bahamian Sandy Beach	1017	9,230
Eastern Caribbean Sandy Beach	2017	1,797
Greater Antilles Sandy Beach	3017	9,128
Bahamian Estuary	1013	2,984

Eastern Caribbean Estuary	2013	368
Greater Antilles Estuary	3013	88,314
Bahamian Coastal Lagoon	1010	17,044
Eastern Caribbean Coastal Lagoon	2010	5,172
Greater Antilles Coastal Lagoon	3010	39,378
Bahamian Manatee	1014	8
Greater Antilles Manatee	3014	139
Bahamian Mangrove	1015	153,947
Eastern Caribbean Mangrove	2015	6,882
Greater Antilles Mangrove	3015	938,917
Bahamian Rocky Shore	1016	159,636
Eastern Caribbean Rocky Shore	2016	686,006
Greater Antilles Rocky Shore	3016	2,285,059
Bahamian Seabird Nesting Area	1018	10
Eastern Caribbean Seabird Nesting Area	2018	7
Greater Antilles Seabird Nesting Area	3018	7
Bahamian Seagrass	1019	5,491,302
Eastern Caribbean Seagrass	2019	276,893
Greater Antilles Seagrass	3019	2,997,601
Bahamian SPAGS High	1022	43
Bahamian SPAGS Low	1020	163
Bahamian SPAGS Medium	1021	327
Eastern Caribbean SPAGS High	2022	135
Eastern Caribbean SPAGS Medium	2021	54
Greater Antilles SPAGS High	3022	246
Greater Antilles SPAGS Low	3020	506
Greater Antilles SPAGS Medium	3021	351

It should be noted that the original intent of this project was to limit the model of marine connectivity between the tri-countries of Cuba, Haiti, and the Dominican Republic. However, upon consulting with marine connectivity experts, it was advised that this limited analysis area would present an inaccurate picture of marine connectivity since the impacts of connectivity of felt far beyond the jurisdictional boundaries of these three countries. It was suggested to enlarge the study area to the entire Caribbean Basin and Gulf of Mexico in order to fully capture the ocean connectivity dynamics that influence this area. Consequently, we followed this advice and gathered coral reef and ocean current data for the entire Caribbean Basin and Gulf of Mexico. Figure 4 shows the two different extents that were used: a) the Caribbean Basin and Gulf of Mexico; and b) the Insular Caribbean. Details of the connectivity and Marxan analyses are explained further in Marxan sections of this report. In summary, these analyses include:

1. An ocean connectivity analysis that simulated coral spawning events for the entire Caribbean Basin and Gulf of Mexico. This analysis used consistently mapped coral reef targets across this area, integrating the connectivity output into a Marxan analysis. Multiple marine targets could not be used in this analysis because they were not available for the entire area.

2. An Insular Caribbean-only Marxan analysis that used multiple marine targets (rather than the single coral reef target) consistently mapped at scale across this smaller area. This analysis did not consider ocean connectivity in the Marxan output solution because a robust connectivity analysis requires a larger area in order to be accurate.

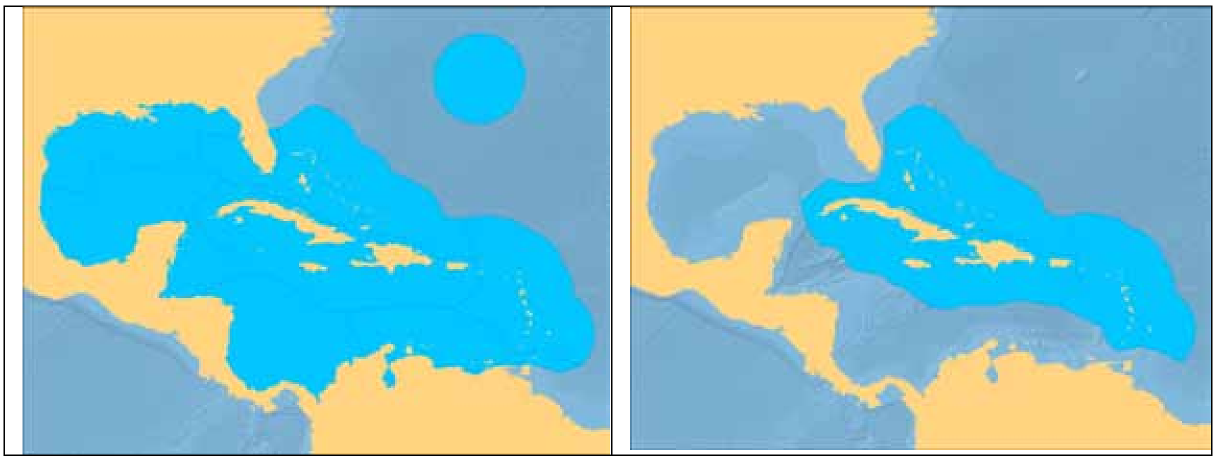


Figure 4. The two different extents that were used: a) the Caribbean Basin and Gulf of Mexico (left); and b) the Insular Caribbean (right).

Table 2. Suggested edits to marine targets and associated response and/or resolutions.

MARINE TARGETS COMMENTS	RESPONSE/RESOLUTION
Explain the criteria that were used for the selection of the marine targets.	An explanation of the criteria used for all marine targets is included in Appendix A.
There is a lack of uniformity in the scales of conservation targets (mixed global data with regional and local data) Example: distribution of marine mammals (too course to be used with other targets)	All data inputs used in the models represent a standardized scale. In order to avoid bias in model output, we had to use consistent data (same scale and method for each marine target) across the Caribbean. In other words, we had to collect the highest resolution marine target data possible using a consistent method across the region. To do this, we used manual digitization from high resolution satellite imagery to capture the majority of the marine targets. Additional details for the creation of the marine targets are explained in Appendix A. We did not use any marine mammal information because the data was either too coarse or inconsistent to be properly applied with the other

	marine targets. Maps showing the distribution of all modeled marine targets can be seen in Appendix B.
There is a confusion of classes derived from the classification of satellite imagery or otherwise overestimation of targets. Example: Nipe Bay should not be classified as an estuary (too much discharge) Example: Imías Maisi not classified as a rocky shore	Confusion of spectral classes is a common problem in satellite imagery classifications. Confusion in classes can only be corrected through long and intensive field work. We did not have the budget to do extensive field work, but provided the opportunity for countries to send updates and improvements in these data based on in-country expert input. Satellite-based mapping requires a balance between accuracy and budgetary constraints. However, we believe we have assembled the most correct and accurate regional database within the budget provided.
Targets were not stratified	We used the expert-defined marine ecoregions (Spalding et al., 2007) to stratify the marine targets prior to setting conservation goals (Figure 1). Ecoregions represent ecologically strong cohesive units, sufficiently large to encompass ecological or life history processes for most sedentary species.
Targets were not screened based on level of risk	We provided the opportunity for the countries to review all targets and screen certain occurrences based on the perceived level of risk prior to incorporation into the model.
Include the following targets: Spawning aggregation sites, Penaeid shrimp (species are of commercial value), dolphins and whales, manatees, seabirds, and seagrass.	We included the following marine targets in our analysis: Spawning aggregation sites, manatees, seabird nesting sites, seagrass. The methods used to map these targets are explained in Appendix A. We did not use Penaeid shrimp as a target because we did not have a regional and consistently mapped location for this target. However, we did use estuaries as a marine target which may coincide with their habitat. We did not use any marine mammal information because the data was either too coarse or inconsistently mapped to be applied with the other marine targets. Maps showing the distribution of all modeled marine targets can be seen in Appendix B.
The following conservation targets have not been identified in the DR: a. Estuaries: Slaughter, the yaks (North and South). b. Coastal lagoon: Quemaito c. Mangroves: Mangroves Juancho d. Laguna: Oviedo, e. Bays: B. Neiba	These marine conservation sites were reviewed and included in the revised analysis.

Consolidation and Refinement of the Marine Threat Model

As one of the world's most environmentally threatened regions, the Caribbean is a complex mix of political and social factors that have taken a heavy toll on marine resources. Deciding how and where to employ conservation actions in the face of multiple, imminent threats is an increasing challenge. The initial step in developing a regional marine threat model was to first consider all threat layers that had previously been created. The initial baseline threat layers contained within TNC's Caribbean Conservation Information System were developed for the TNC's Caribbean Ecoregional Assessment (Huggins et al., 2007) and represent a consistent region-wide mosaic of relative human impacts on marine resources and consider coastal development, tourism expansion, sediment and pollution from inland sources, marine based pollution, and pressure on fisheries. Many of these baseline threat layers came from Burke and Maiden's Reefs at Risk work in 2004. All threat layers were integrated with the 1 km cell global marine threat model developed by Halpern et al. (2008). This threat model represents the cumulative impact and corresponding marine ecosystem vulnerability scores of 17 categories of anthropogenic drivers of change developed through expert workshops and include the following:

Artisanal Fishing	Demersal Destructive Fishing	Demersal Non-Destructive, High-By catch Fishing	Demersal Non-Destructive, Low-By catch Fishing
Inorganic Pollution	Invasive Species	Nutrient Input	Ocean Acidification
Benthic Structures (Oil Rigs)	Organic Pollution	Pelagic High-By catch Fishing	Pelagic Low-By catch Fishing
Ocean-Based Pollution	Population Pressure	Commercial Activity (Shipping)	Climate Change (SST)

In summary, the steps for creating the global marine threat model were as follows:

1. Compilation or creation of different types of human activities that directly or indirectly have an impact on the ecological communities in the ocean's ecosystems. In total, 17 different activities in categories like fishing, climate change, and pollution were used (listed above).

2. To estimate the ecological consequences of these activities, an approach was created to quantify the vulnerability of different marine ecosystems (e.g., mangroves, coral reefs) to each of these activities (Halpern et al., 2008). For example, fertilizer runoff has been shown to have a large effect on coral reefs but a much smaller one on kelp forests.

3. The cumulative impact map was created by overlaying the 17 threat maps onto the ecosystems, and using the vulnerability scores to translate the threats into a metric of total ecological impact.

4. Finally, using global estimates of the condition of marine ecosystems from previous studies, the impact scores were ground referenced.

More information on the descriptions of the methods that were used to create each individual threat inputs for the global marine threat model can be read in Halpern et al. (2008). All open-access data and analytical code used in the global marine threat model can be downloaded at http://www.nceas.ucsb.edu/GlobalMarine.

A normalization grid function was applied to TNC's threat layers to adjust and combine the values to the same scale as the global threat layers. The resulting marine threat model represents the most detailed and comprehensive model based on the aggregation of available regional threat data. This draft marine threat model was presented at the October Caribbean Biological Corridor workshop and representatives from each country had the opportunity to provide comments and suggest edits. The Table 3 lists all suggested edits and associated response and/or resolution actions that were taken. Once the marine threat model was edited and finalized, the mean threat value (or "cost" in Marxan terms) was calculated for each overlapping planning unit using zonal spatial statistics in GIS. This extracted cost score was then assigned to each unique planning unit ID in the pu.dat Marxan input file. Planning unit cost is one of the cost values (in addition to the penalty factor and boundary length modifier) that the Marxan optimization algorithm uses when identifying "efficient" solutions to conservation goals. All marine threat models and synthesis into planning units maps, showing average threat value by planning unit, is shown in Appendix B. Areas of red indicate high threat, yellow indicates medium threat, and blue represents lower threat levels- or areas where the accumulation of the input threat layers was minimal.

Table 3. Suggested edits to marine threat model and associated response and/or resolutions.

THREATS COMMENTS	RESPONSE/RESOLUTION
Please include a general diagram of threats that shows the interactions between activities and the objects on which they act.	A summary explanation of how the threat layers have been combined is included in this final report. Additional details can be found in reading *Huggins et al. (2007)* for TNC's marine threat layers and *Halpern et al. (2008)* for the global marine threat layers.
The global scale of threats is difficult to apply to a regional setting; consequently, some sources of information used to generate the threat surface are overestimated. Example: Cuba shows nearly 80% agriculture when this is not the case.	We used raster modeling to make the adjustments and refinements to the threat layers as recommended at stakeholder workshops.
It is necessary to simplify the map of threats to make the analysis more reliable. The map with all the threats together impedes analysis.	Our intent was to identify and aggregate the most detailed and systematic threat layers available at a regional scale. As all inputs have previously been peer-reviewed by experts, they represent the most accurate threat models available. Any attempt to simplify these layers would diminish the accuracy of our results.

Marine Corridor Modeling- Coral Larval Dispersion and Settlement Simulation

Marine corridor and connectivity modelling has evaded most marine conservation projects due to the high level of sophistication of the model, availability of the data, and the expertise needed to successful set up, run, and interpret the results. Fortunately, this project greatly benefited from the expertise and close collaboration of Dr. Eric Treml from the University of Queensland and Dr.

Jason Roberts from Duke University, well-published experts in ocean connectivity and larval transport modelling. Given the limited budget and time frame of this project, we did not have the luxury of modelling marine connectivity for a wide range of species and life cycles. This research specifically focuses on coral connectivity in the highly connected Caribbean Basin and Gulf of Mexico - the heart of Atlantic tropical marine biodiversity. However, the broad patterns of marine connectivity developed for this project can also applied to a variety of other spawning marine species. The marine connectivity and larval transport models produced explore research questions such as:

Following a spawning event, where do coral larvae go?
Where is settlement and recruitment most likely to occur?
How dependent is each country on other country's reefs?
Where are the core networks of marine connectivity within the Caribbean and are they protected and managed?

To help answer these questions, we developed a regional ocean connectivity model (8x8km) for the Caribbean Basin and Gulf of Mexico, integrating the ocean current information in NOAA's Real-Time Ocean Forecast System (RTOFS) [http://polar.ncep.noaa.gov/ofs/]. The RTOFS-Atlantic system has been operational since December 2005 and is the first real-time ocean forecast system based on the Hybrid Coordinate Ocean Model (HYCOM) ocean model (http://hycom.org) (Bleck, 2002). It runs daily and provides one-day and six-day forecasts of the Atlantic basin which extends from 25°S to 72°N and from 98°W to 16°E. Preliminary evaluations of model performance indicate that predictions compare well to historical observations but are only partly able to capture the daily variability of mesoscale features, fronts and associated transports (Mehra and Rivin 2010). Improvements to RTOFS relative to HYCOM include a finer spatial sensitivity to currents - enough resolution to resolve the oceanic response to large severe storms such as hurricanes or large wind events. This behaviour is attributed to a superior spatiotemporal resolution of the underlying forcing data (3hr and 25km cell). ROTFS also incorporates the tide cycle which improves reliability of current direction and velocity.

Prior to setting up and running the larval dispersion models, several biological parameters that define the larvae biological characteristics and behaviour had to be considered. These parameters influence the dispersion, settlement, and recruitment rates calculated in the model. Estimated values for each of these parameters were recommended by Drs. Treml and Roberts based on previous experience and past research. The values that were used represent characteristic average values for coral larvae found in the Caribbean. Each of these parameters, definitions, and values can be found in Table 4.

Table 4. Larval biological parameters that were considered prior to running the dispersal simulations.

Larval Biological Parameter	Description	Value
Time and frequency of	More spawning opportunities have	We performed eight dispersal

spawning (e.g. lunar, annual)	significant implications on the local-to-regional connectivity patterns.	simulations--two per year--that started on the dates of the last quarter moon -based on observations of coral mass spawning events in the Caribbean. 23 August 2008 22 September 2008 13 August 2009 12 September 2009 1 September 2010 1 October 2010 21 August 2011 20 September 2011
Maximum number of days alive	This is called the Pelagic larval duration (PLD) and the longer the duration, the greater the potential for long-distant connections.	We used a maximum PLD of 30 days, typical for most coral larvae. Model results can be time-stepped and extracted for any species with a shorter PLD
Pre-competency period estimation	This is often between 2-7 days for many fish/inverts, but can be up to 50% of PLD. This has a large impact on local-scale patterns (local retention, self-recruitment and local-scale connections).	Following Treml et al. (in review), larval competency was modeled using a gamma cumulative distribution function that allowed all of the larvae to reach full competency in 3 days.
Ability to sense local proximity of reefs	Sensory zone behaviour influences local-retention & self recruitment, but little impact on the relative regional connectivity patterns.	We assumed that larvae could not sense reef proximity
Settlement behaviour	Probability of larvae settling if they encounter suitable habitat. Typically 50-95% proportion will settle. Model output and patterns are not very sensitive to settlement behaviour, but having a high value (like 90%) or low value (like 50%) makes some biological sense for some species.	After reaching competency, when larvae drifted over coral habitat they settled at a rate of 75% per day (i.e. if 100 larvae were suspended over habitat for 1 day, 75 of them would settle there).
Local density and fecundity	The migration rate threshold (MRT) represents a critical recruitment level used in determining what connections are meaningful or relevant (Cowen et al. 2006). This limit may be in terms of the proportion of successful settlers or a required number of successful larvae, and provides a method for separating evolutionarily relevant connectivity from demographically significant levels (Cowen & Sponaugle 2009, Table S5). Our modeling approach provides the precision required to investigate connectivity along this entire gradient from	The amount of larvae released was proportional to the amount of reef area.

	ecological to evolutionarily-significant levels.	
Larval mortality	This daily mortality rate has a large impact on the local-to-regional strengths of connectivity, but little impact on the overall structure, unless a threshold (connectivity or migration rate) is used to define a lower limit. Mortality, along with density and fecundity, impacts the structure of strong/demographic connections.	Larval mortality was not considered; all larvae were permitted to survive until they settled or until 30 days elapsed, at which point they were assumed to be lost.
Threshold to define a 'meaningful' connection	Estimated to be 1/1,000,000 larvae or the probability of .000001 for a successful dispersal connection. In other words, only levels of connectivity above this threshold are considered. The local density and fecundity should be considered when defining this threshold. Higher larval output should result in a smaller threshold for 'demographically relevant' connectivity.	We used an example of 1/1,000,000. A larger value (e.g. 1/1,000 larvae) will produce fewer connections; these connections may be "demographically relevant" (i.e. relevant to maintaining populations over short time scales) compared to the weak connections, which tend rather to be "evolutionarily relevant" (they maintain the species overall range and impact evolution)

Selection of the Reef Data and Reef Units

Using the two-dimensional hydrodynamic larval dispersal framework described by Treml et al. (in review) and applied by Mora et al. (2012), we simulated the movement and settlement of coral larvae for the years 2008-2011 throughout the Caribbean Basin, Gulf of Mexico, and southwest Sargasso Sea (8-35 N, 56-98 W). These dates represent the total time period available for the RTOFS dataset. Our first step was to assemble a comprehensive map of the locations of coral reefs throughout the study area using data from the Millennium Reef maps (Andréfouët et al., 2005). Prior to using these data in the model, all coral reef locations were reviewed and edited by in-country reef experts. Next, we used a combination of automated and manual processes that followed the methods of Treml et al. (2008) and Mora et al. (2012), to develop a reduced resolution (8km) gridded version of these reef locations and grouped contiguous clusters of coral habitat into 423 distinct reef units. We determined that the processing time required for the model would not be practical if more than about 500 reefs were present. Given the local spatial scale and close proximity of the reefs within each reef units, it was assumed that each unit was highly internally connected.

Extraction of the Reef Abundance by Reef Units

We derived three datasets in preparation of running the model (i.e. of the two-dimensional hydrodynamic larval dispersal framework required the following described datasets). The first was a gridded dataset that coded a unique ID associated with each of the distinct reef patches. The second was a gridded dataset that represented the proportion of the area in each cell considered to be reef. This was accomplished by utilizing the original reef dataset and overlaying it with the gridded dataset. The third dataset was simply a land-water mask that was used to define land boundaries.

Running the Connectivity Model

We then performed eight dispersal simulations--two per year--that started on the dates of the last quarter moon in August and September (23 August 2008,22 September 2008, 13 August 2009, 12 September 2009, 1 September 2010, 1 October 2010, 21 August 2011, 20 September 2011). We selected these dates based on observations of coral mass spawning events in the Caribbean reported by van Woesik et al. (2006, Supplemental Information), Bastidas et al. (2005), and Medes and Woodley (2002).

At the start of each simulation, the hydrodynamic model released larvae at the ocean surface above each of the 423 reef units and allowed them to drift with the ocean surface currents. The quantity of larvae released was proportional to the abundance of coral habitat at each 8km grid cell. For ocean currents, we used hourly estimates from the Real Time Ocean Forecast System (RTOFS) (Mehra and Rivin, 2010), which integrates a number of physical processes including geostrophic currents, Ekman (wind-driven) transport, and tides. Larvae were allowed to drift for 30 days (i.e. the pelagic larval duration (PLD) was 30 days). Following Treml et al. (in review), larval competency was modeled using a gamma cumulative distribution function that allowed all of the larvae to reach full competency in 3 days.

After reaching competency, when larvae drifted over coral habitat they settled at a rate of 75% per day (i.e. if 100 larvae were suspended over habitat for 1 day, 75 of them would settle there). Larval mortality was not considered; all larvae were permitted to drift until they settled or until 30 days elapsed, at which point they were assumed to be lost. Mortality is an important factor that will make short connections much stronger relative to long connections.

Creating the Network

At the end of each simulation, we tallied the quantity of larvae transported between each of the 423 reef units, including larvae that settled on their natal patch (so-called self recruitment), for a total of 178,929 possible connections. These files were processed first to flat files (Comma Separated Values, See Figure 5) and then, using the centroid of each reef unit, we drew a connection between each connected from-to reef pair (Figure 6a-b). The output value representing the quantity of transported larva was calculated in cell units. For example a value of 2.95 can be interpreted in the following manner: 2.95 cells (in our case a cell was an area of 8km x 8km) worth of larva traveled from the from-reef and settled on the to-reef (see Figure 5 again). In addition to the Dispersal value shown in here, we calculated an additional value for each connection. This value is the proportion of the dispersal value divided by the total amount of larva released from that reef (the “From” reef). This was actually the value we used later as the modification of boundary length in Marxan and the value symbolized in Figure 6a-b below. Finally, after we processed all the output datasets into shapefiles, each output dataset was averaged to produce a single “all connections” dataset.

The strength of each connection was then used to modify the boundary length of the planning units in the Marxan bound.dat input file, causing the output portfolio solutions to cluster on strong connections between reef units. Table 5 lists the suggested edits to the draft connectivity models that were presented at the stakeholder workshop along with the associated response and/or resolutions that were taken. This method is explained in greater detail in the next section. Example maps of the connectivity model output are shown in Appendix B and also can be viewed from the following site http://bit.ly/IIZNXE

FromReef	ToReef	Dispersal
1	1	2.95766
2	2	0.00311209
2	3	0.000366731
2	4	0.00966152
2	5	0.0113958
2	6	0.00113246
3	2	0.000457574
3	3	0.0743045

Figure 5 – A screen capture of the initial reef connectivity file (a comma separated file shown in MS Excel.)

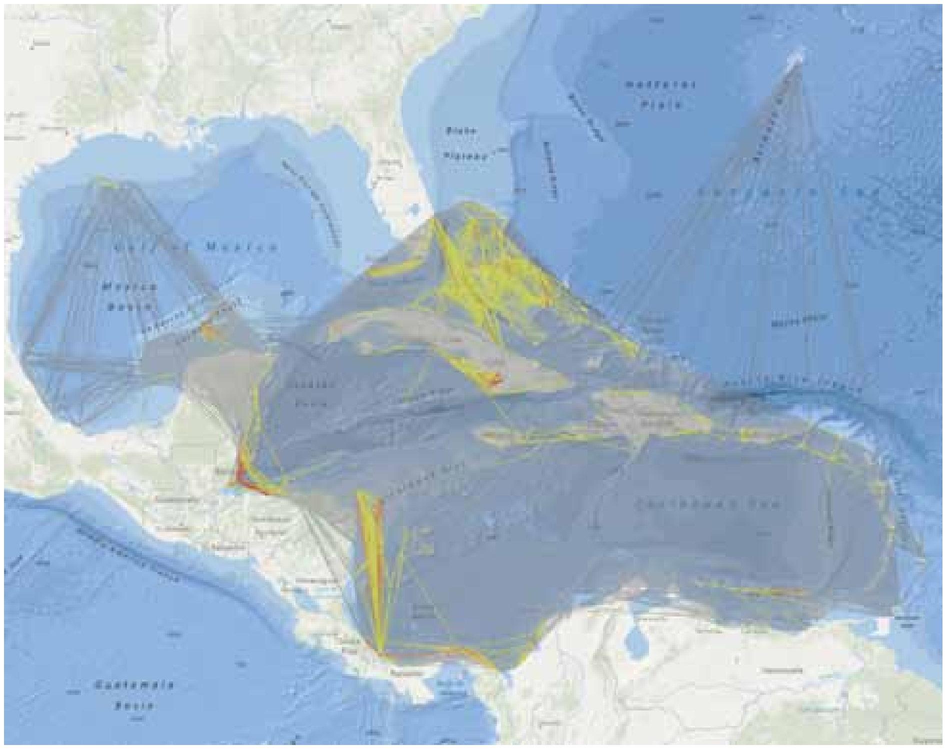


Figure 6a – The modeled reef connections. All connections are shown in transparent grey. The strongest connections (measured using the proportion number described in the text) are shown in range from yellow-orange-red (Modeled using ROTFS data between the years 2008-2011).

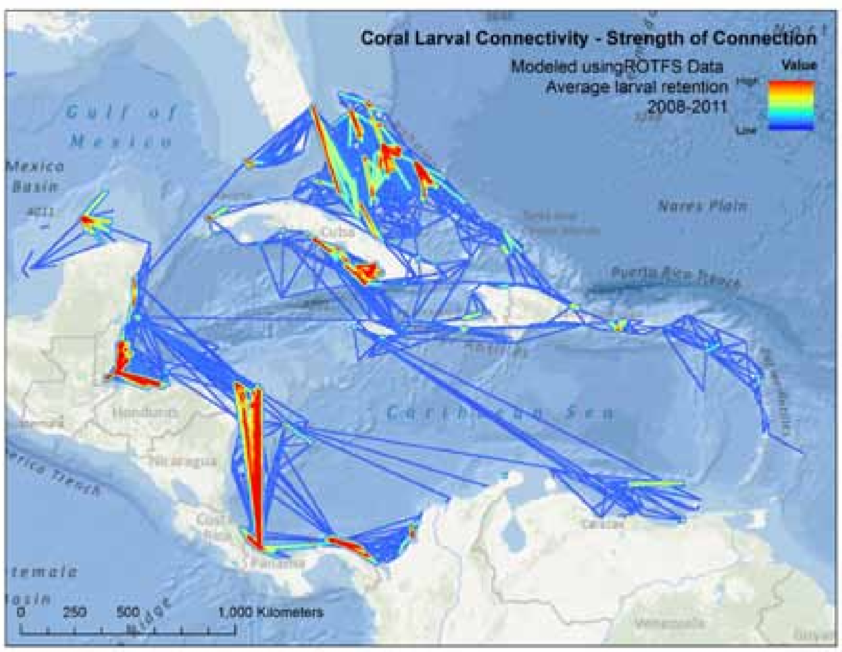


Figure 6b – Another visualization of the connectivity results with the strongest settlement connections shown in red and yellow hues. These values represent average connection strengths modeled using ROTFS data between the years 2008-2011.

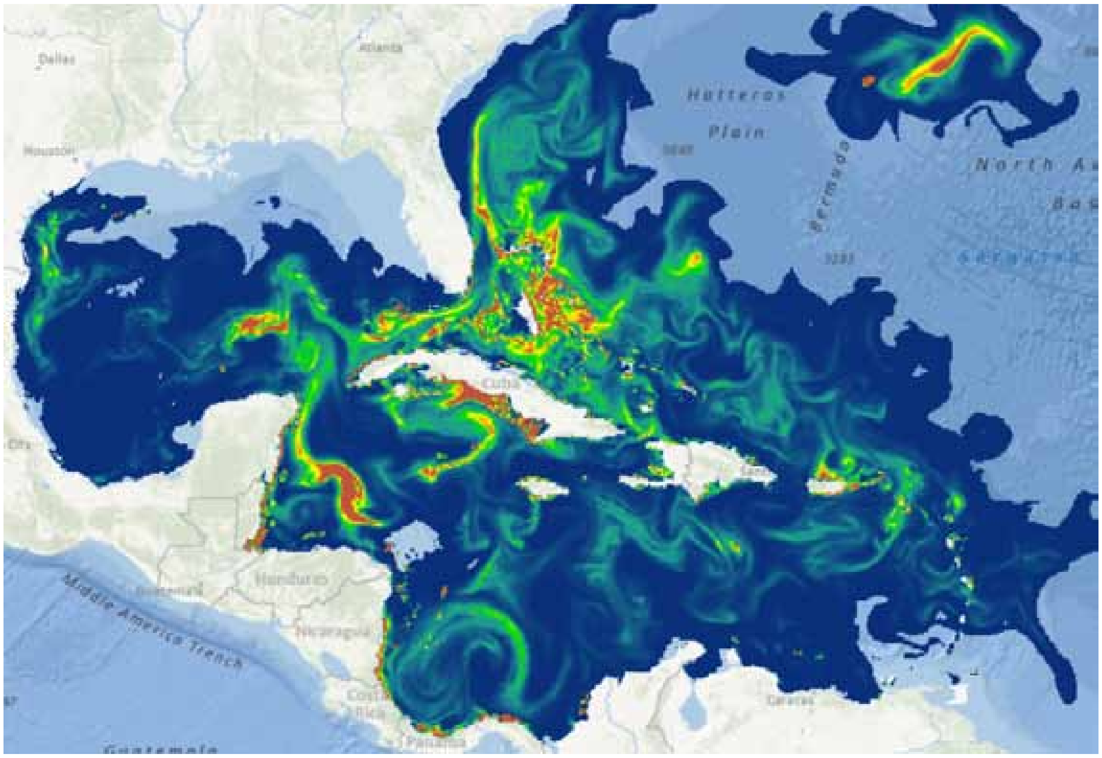
Table 5. Suggested edits to the connectivity model and associated response and/or resolutions

CONNECTIVITY	RESPONSE/RESOLUTION
Dispersal of larvae of different species including spiny lobster and queen conch	The project did not have the time or budget to explore the dispersal patterns of other species. However, if species characteristics are similar to coral larvae, the results could be investigated on a day-by-day basis up to a maximum PLD of 30 days.
Strengthen connectivity data by including the theory of genetic drift between different species lineages	Our project did not have the data and time needed to research the theory of genetic drift. With increased funding and time in a second phase for the project, those ideas could be explored.

Larval Transport Animations

Output from larval transport models are most easily understood and visualized through the creation of video animations that show the day-by-day dispersion patterns. As one of the deliverables for this project, a series of videos in AVI format were created that show the dispersion of larvae across the Caribbean Basin and Gulf of Mexico for each specified spawning event. The animations were created using uncompressed frames in ArcGIS version 10. An example video for the spawning event that occurred on August 21, 2011 can be downloaded at http://tnc.usm.edu/mrc/LarvalDensity_2011_08_21.avi A frame of this video can be seen below. Please note that downloading these files may require a significant amount of time and bandwidth since each file is approximately 400MB in size.

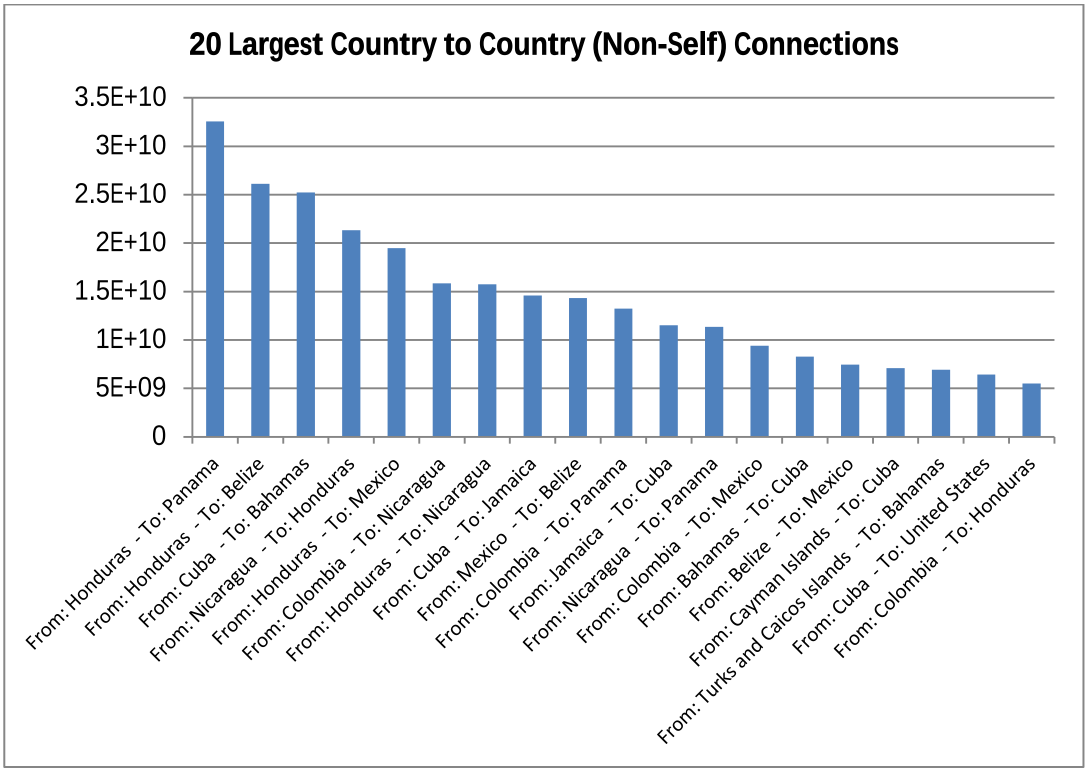
When viewing the animations, the shimmering/pulsing movement often observed is attributed to tidal cycles which are captured by the ROTFS data. These effects are observed less in the Gulf of Mexico and Caribbean Basin where the geography of those basins yield weak tides. Another unique and exciting characteristic of the ROTFS data is its ability to capture the effects of hurricanes and other extreme wind events. These events can be seen in the animations as moving "wavelike" ripples. For example in the 20 September 2011 video, you will notice a strong ripple that moves past the north side of Puerto Rico, D.R., and the Bahamas, around 1 second into the animation. This ripple is caused by the passage of Hurricane Irene. Caution must be taken when interpreting larval dispersion in the presence of large storms as accuracy may be compromised. Some research points to the fact that large storms have the potential to sink what's floating at the surface and the model certainly does not account for that. Nonetheless, it is interesting to see that RTOFS appears to incorporate these extreme events, and they play out in the simulation (Roberts, 2012).



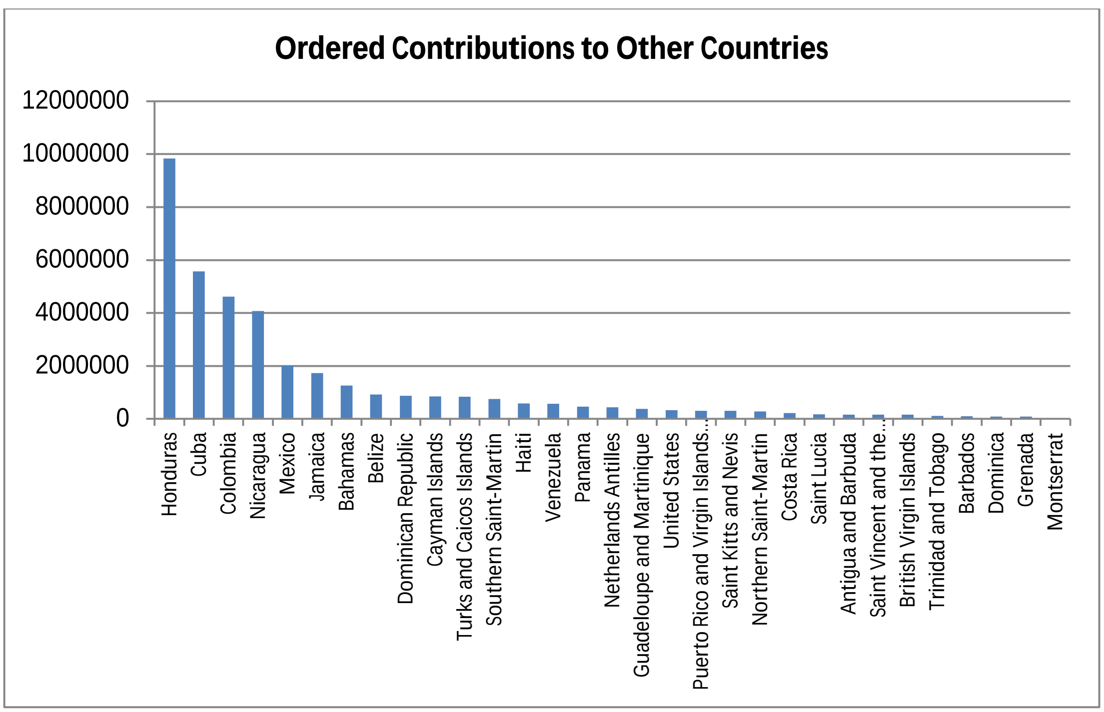
Video frame of one of the larvae dispersion animation showing a spawning event that occurred on August 21, 2011.

Results

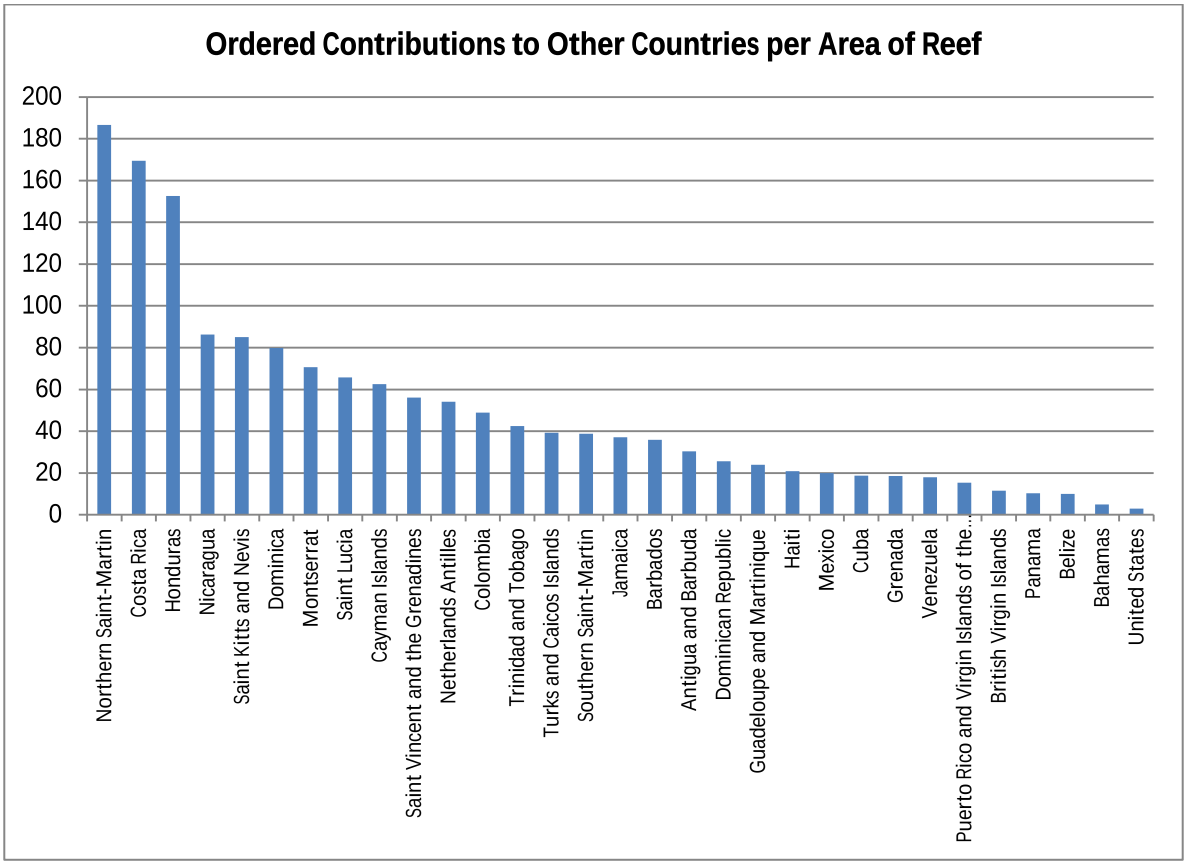
The coral connectivity work conducted in this research, takes advantage of new oceanographic data and computer simulations programs, offering new insight into how corals are connected throughout the region. These models permit the tracking of larvae following a spawning event in a very precise manner integrating weather and tide cycles that increases the accuracy and reliability of the model. These patterns can be analyzed to determine where settlement and recruitment are most likely to occur along with estimations on how dependent each country is on the health of corals in neighboring countries where larvae may originate. To do this, we used the Exclusive Economic Zones (EEZ) for each country and calculated the coral retention using the *From* and *To Reef* attributes in the model output. The graphs below show interesting patterns in how ocean currents and coral abundance can influence how countries contribute to each other's coral reef ecosystem. Based on the model, the first graph shows the top twenty strongest country-to-country connections based on how much estimated coral larvae is contributed to the receiving country. The second graph shows the top twenty countries ordered by how much estimated total coral larvae are contribute to other country's coral reefs. Appendix B shows the individual results of a country-by-country larvae retention rate analysis as reported for the countries of the Insular Caribbean. In other words, it shows for coral larvae retained within a particular country, what country they came from. The complete numerical report with all the underlying data can be found in the excel spreadsheets that are accompanied with this report. In addition to the bar charts, the spreadsheet also contains pie charts showing the allocation of larvae retention percentages by country. You will notice that some countries, like Cuba, have high rates of self-retention – meaning that the large majority of larvae produced remains within the jurisdictional waters and does not migrate or settle within another country. This is the case for the majority of countries, where larvae originates and settles in the same country or is received by only a few others. However, there are countries like the St. Kitts and Nevis or Costa Rica, that are highly dependent on larvae coming from multiple countries or jurisdictions. The maps below the bar graphs are maps from Cuba, Haiti, and the Dominican Republic that show model results indicating a) outside each country's marine jurisdiction, what countries do coral larvae come from (e.g. Outside of Cuba, where do Cuba's coral larvae come from?) and; b) in what countries do a particular country's coral larvae settle (e.g. in what countries do Cuba's coral larvae settle?) These model results can be a powerful multi-jurisdictional tool for understanding dependency between countries and using it as a basis for improving marine management across jurisdictional boundaries. Knowing where and which countries are contributing to the health of a country's coral can help foster regional cooperation and the strategic expansion of marine protected areas that maintain marine connections within key corridors. Ultimately, this research identifies core network areas and helps the marine science community better understand connectivity, metapopulation dynamics, and the utility of marine protected areas that will improve marine resource stocks and foster better, more coordinated management.



This chart shows the largest country to country summed total amount of Larvae over all the simulated periods that are not self contributions (i.e from and to countries are not the same)



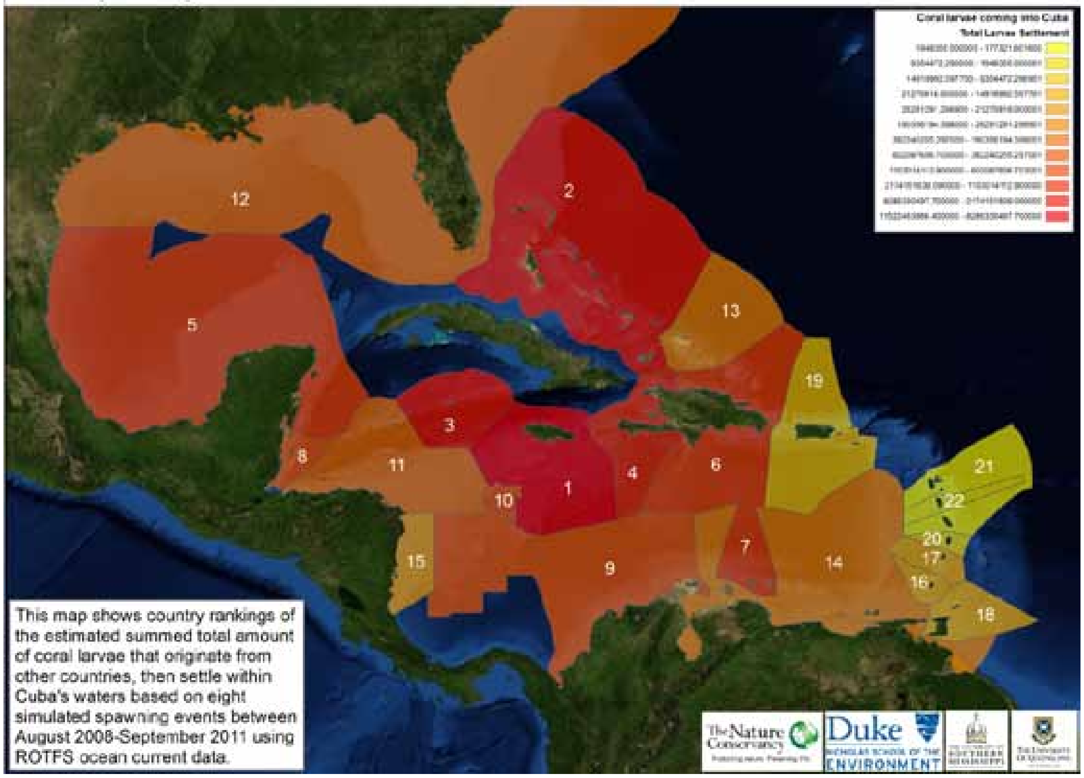
This chart shows all the counties contributions in total larvae to any other country. The two countries that did not have significant contributions to other countries were Anguilla and Bermuda.



This chart shows all the counties contributions in total larvae to any other country, but reef area normalized (Exclusive Economic Zone (EEZ) divided by reef area). Reef area was used to determine larvae dispersed so another way to describe this chart is that it shows contributions to other normalized by the amount of modeled larvae dispersed. The two countries that did not have significant contributions to other countries were Anguilla and Bermuda.

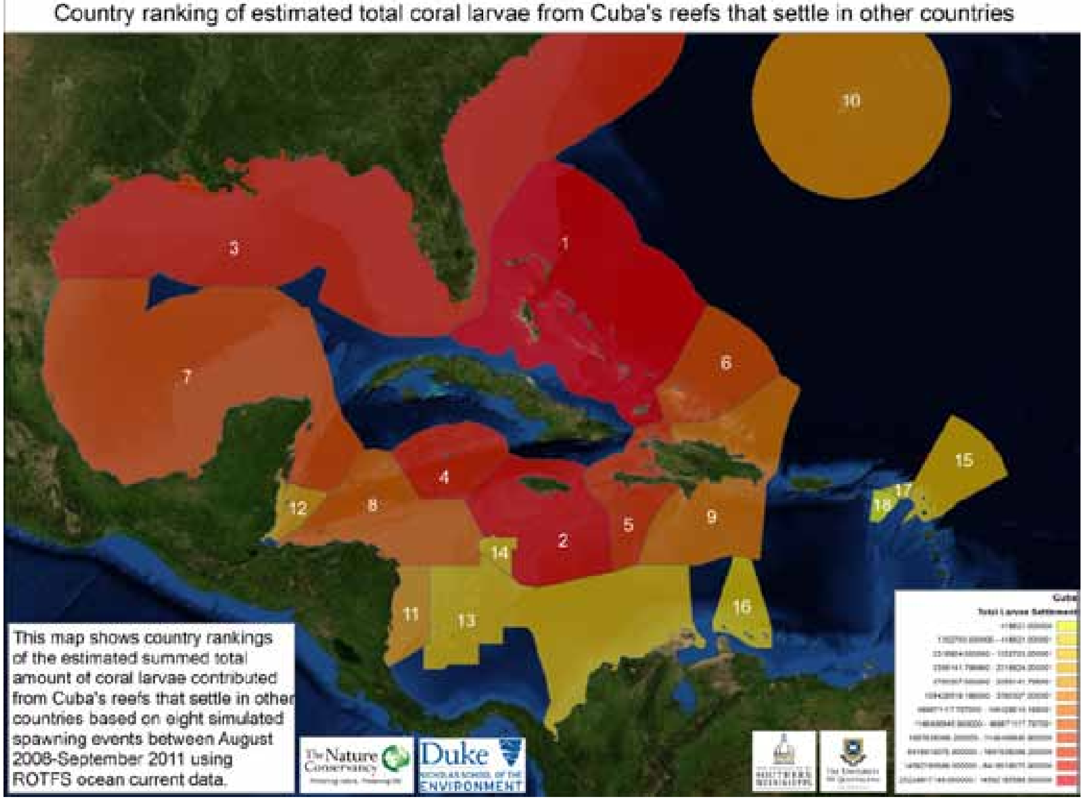
Outside of Cuba, where do Cuba's coral larvae come from?

Country ranking of estimated total coral larvae received from other countries and settle within Cuba



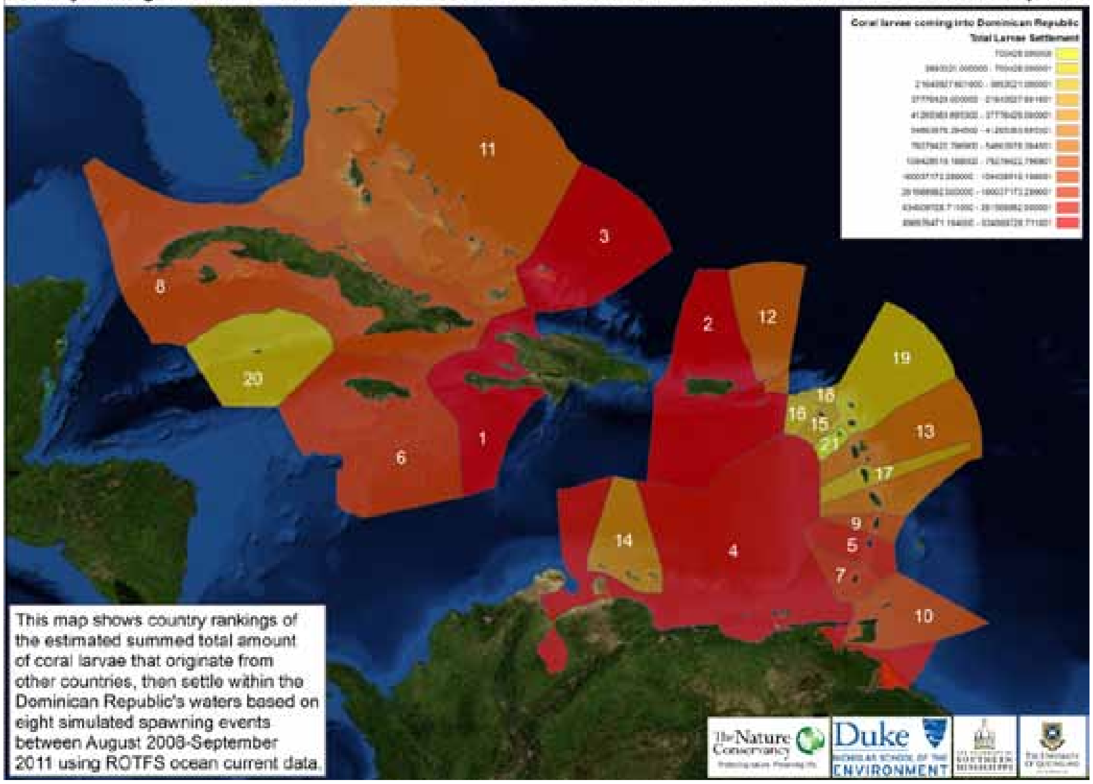
In what countries do Cuba's coral larvae settle?

Country ranking of estimated total coral larvae from Cuba's reefs that settle in other countries



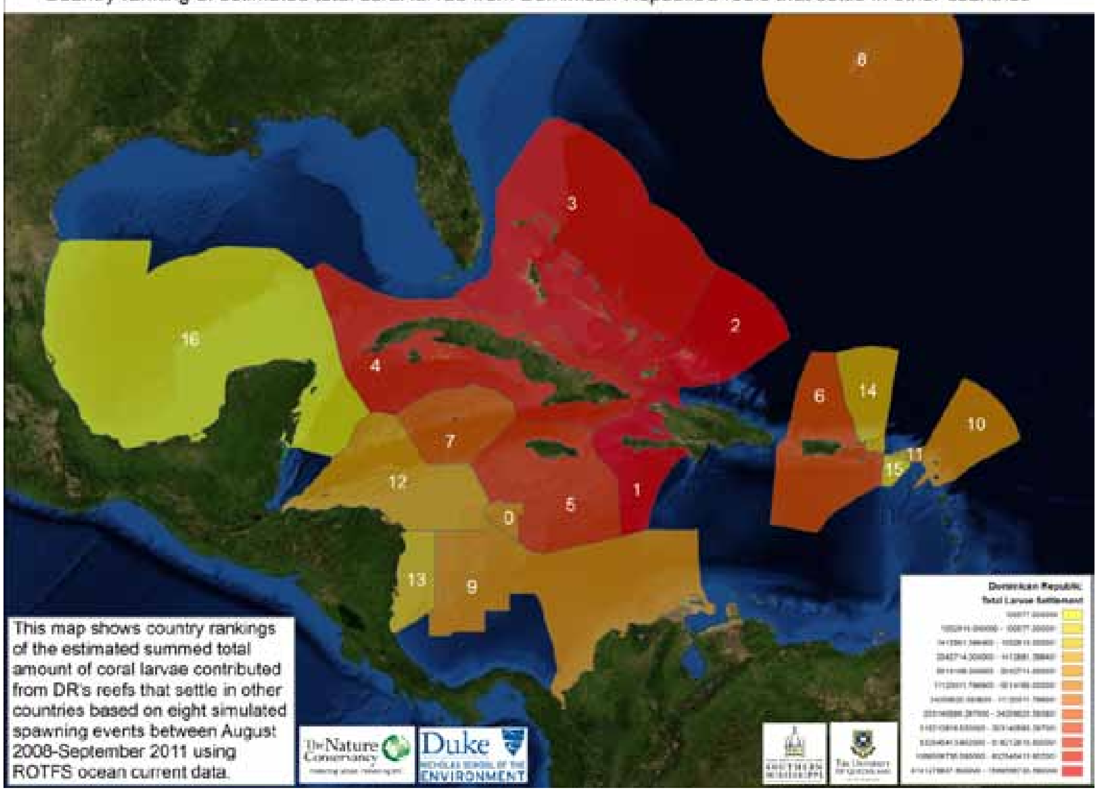
Outside of the Dominican Republic, where do the Dominican Republic's coral larvae come from?

Country ranking of estimated total coral larvae received from other countries and settle within the Dominican Republic



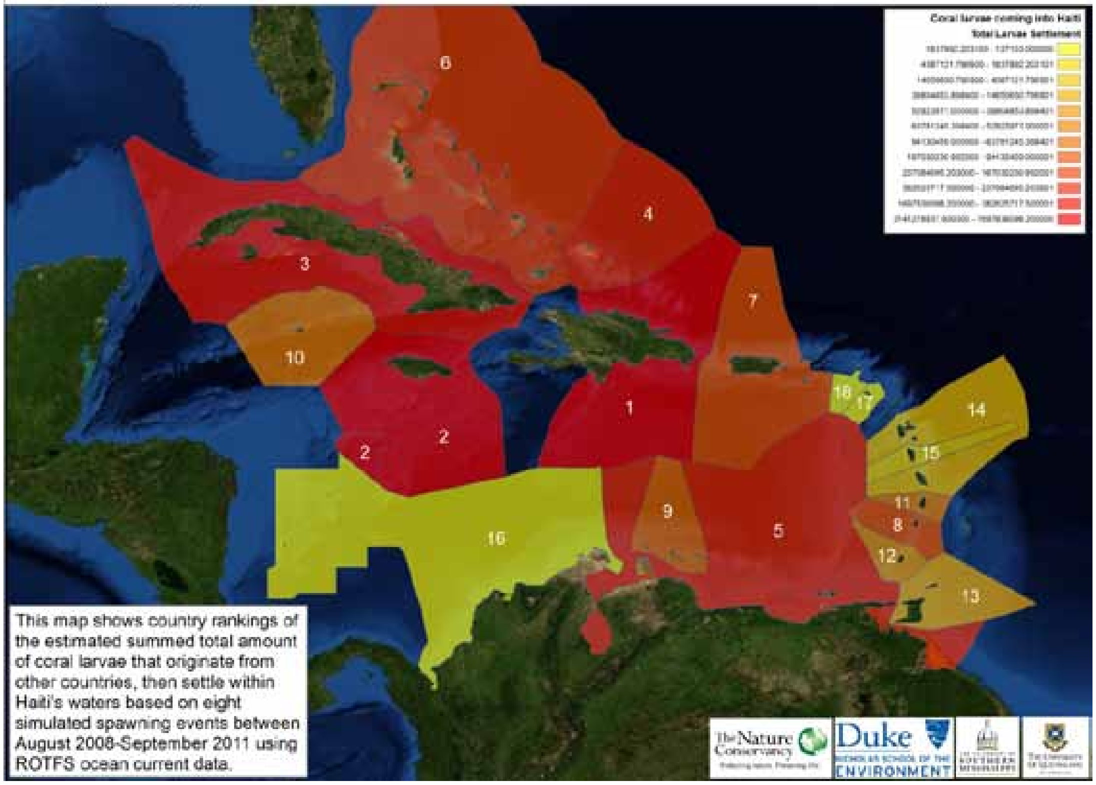
In what countries do Dominican Republic's coral larvae settle?

Country ranking of estimated total coral larvae from Dominican Republic's reefs that settle in other countries



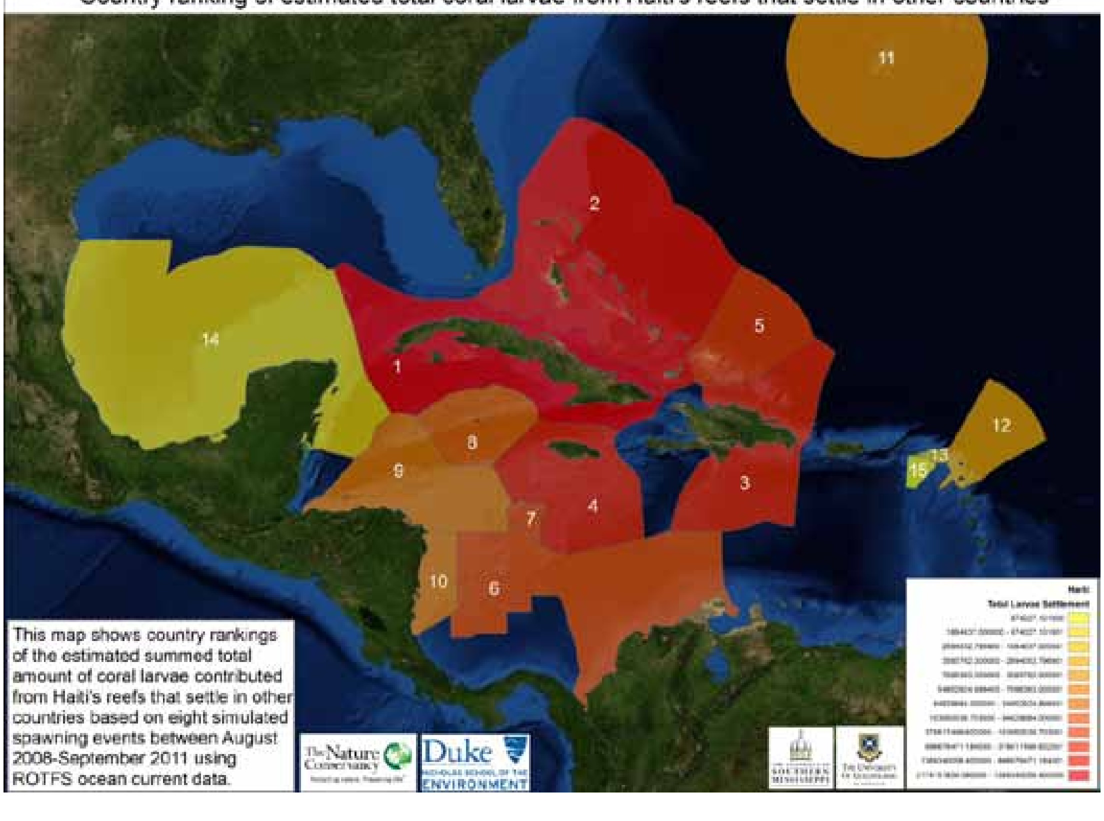
Outside of Haiti, where do Haiti's coral larvae come from?

Country ranking of estimated total coral larvae received from other countries and settle within Haiti



In what countries to Haiti's coral larvae settle?

Country ranking of estimated total coral larvae from Haiti's reefs that settle in other countries



Site optimization and the selection of a marine conservation portfolio

Early conservation assessments depended on manual mapping to delineate sites and were often reliant on expert opinion to prioritize conservation areas. The large number, size, and diverse types of datasets describing the targets eventually required the use of a more systematic and efficient site selection procedure. The site selection program Marxan (Ball et al., 2009) is widely used for systematic conservation planning and helps to answer the question, "What areas are the most important to protect?" The program does this by considering multiple ecological features and threat factors, then provides a 'best' or most efficient portfolio of conservation areas based pre-set goals, underlying "costs," and many independent model runs. The areas chosen most often are considered the highest priority to include in a conservation area network design based on their biological richness, (e.g. the presence of large numbers of conservation targets) and high suitability scores. Using a transparent process that is driven by quantitative goals, the analysis is repeatable and objective. Marxan results can illustrate a pattern of priority sites of low political or social pressure that can still satisfy the explicit biodiversity goals. It can also identify a network of sites where resources necessary to implement conservation strategies or threat abatement are forecast to be lower.

A unique aspect of our approach is we will be using Marxan to consider the influences of dynamic ocean currents within the Caribbean Basin and Gulf of Mexico. Since marine connectivity plays an important role for safe guarding the life cycle of many important marine species, it is critical that this information be utilized in the expansion of MPA networks throughout the region. Table 6. Suggested edits to the Marxan analysis and associated response and/or resolutions that were taken.

Table 6. Suggested edits to the Marxan analysis and associated response and/or resolutions

MARXAN	RESPONSE/RESOLUTION
Include connectivity in the Marxan runs	A suite of Marxan scenarios that integrates the coral connectivity information was included as part of the analysis. For maps of model output, please see Appendix C.
Show how you calibrated the model parameters, such as the BLM – include a graph showing the calibration report	Information on model calibration of Marxan and all the parameters used is described in the Marxan section of this report.
Include all Marxan output reports to demonstrate which goals were met and parameters used.	All Marxan output reports (MVBEST.TXT and SUM.TXT) are included in Appendix C.

Marxan Parameters

Marxan software requires the user to specify multiple parameters that control the model output. The parameters that were specified for the Caribbean Biological Corridor analyses include: number of repeat model runs, boundary length modifier ("BLM", influences spatial contiguity of the model results), algorithm type (and additional parameters specific to the chosen algorithm), status of input planning units (whether a planning unit is a model seed, locked in, locked out, or unconstrained), the "cost" of selecting any particular planning unit for inclusion in the final portfolio), and the specific representation goals for each conservation target. Below is a list of the major parameters that were specified for the Marxan model runs:

GOAL: 20% all marine targets

REPETITIONS: 100

ITERATIONS: 1,000,000

SCENARIOS:

A. Insular Caribbean: With cost model and PROTECTED AREAS locked in
B. Insular Caribbean: With cost model and no PROTECTED AREAS
C. Caribbean Basin and Gulf of Mexico: With cost model and PROTECTED AREAS locked in
D. Caribbean Basin and Gulf of Mexico: With cost model and no PROTECTED AREAS

BOUDNARY LENGTH MODIFIER (BLM): 1 (calibrated using cost vs. boundary length)

TARGETS (features and methods for mapping described in Appendix A)

THREATS (layers used for creating the cost model and methods described in Appendix B)

One of these parameters in particular, the Boundary Length Modifier (BLM), strongly influences the spatial configuration of the planning units that are selected as the solution set of the model. High BLM values force the clustering of the solution set, whereas low BLM values allow for a more fragmented set of planning units to be selected as a model solution. This parameter has been the subject of much discussion regarding the proper values to specify for a given analysis. There is no hard and fast rule as to what BLM value makes the most sense in a given situation. The level of clustering that makes the most sense depends on the objectives of the analysis. Some features of interest for conservation may be best protected in many disjoint reserves, where as others are best protected in large contiguous areas on the landscape. The actual value that is specified for the BLM parameter is somewhat arbitrary and must be decided upon through a process of trial and error. The following is a brief discussion of the rationale behind the use of BLM values for these terrestrial Marxan runs.

The Marxan objective function is to minimize the overall "cost" of a "portfolio" of planning units, where cost is measured as:

Σ (boundary length cost * BLM) + Σ(planning unit cost) + Σ(target penalty cost)

Theoretically, Marxan will choose the set of planning units that best minimize all of these types of cost, while simultaneously solving for the various target representation goals. The BLM (boundary length modifier) parameter is the multiplicative factor that is used in order to convert units of boundary length to a range that more closely matches the other cost units in the model. If the units of boundary length are much larger than the units of planning unit (PU) cost, then the Marxan output will appear spatially clustered. In this scenario, selecting a solution set that minimizes total boundary length more efficiently reduces the overall cost of the solution than does simply minimizing the selection of planning units that have PU costs associated with them. One side effect of forcing a clustered result through the application of a high BLM is that many planning units that have high PU cost may also be included in the solution set. Conversely, if the units of PU cost are much larger than the units of boundary length, then Marxan will get a better reduction in overall cost by minimizing the number of units that have high levels of PU cost. The PU cost would then override any potential clustering effect from the BLM, and the solution may be more fragmented spatially (this may or may not be the case, depending on the spatial configuration of the units with high PU cost).

The relationship between the size of the boundary length units and the units of PU cost determines whether the model will strongly avoid solutions with high boundary cost, or avoid solutions with high PU cost. Since the actual PU cost values may be non-intuitive, the decision of how best to scale these units relative to each other can be difficult to make, and generally involves trial and error. We assumed that, in most cases, a PU that is added to an existing cluster of 2 or more PUs will share two edges with the existing cluster, as shown below.

If that planning unit has PU cost associated with it that is much greater than 2 edges worth of boundary length, then the model may avoid that PU regardless of the potential loss of 2 edges worth of boundary cost. It may be less costly to choose a stand-alone PU that adds 6 edges worth of cost, but has less PU cost. The approach we took was to initially parameterize the Marxan runs using a BLM that balances *2 edges* of boundary length to the *median* PU cost (human impacts) found across all of the planning units. The assumption is that 1/2 of the units will have enough cost to override the clustering effect, and 1/2 of the units have too little cost to override the clustering effect. This BLM level should yield a result that balances the efficient representation of targets (at the desired goal levels) with the avoidance of planning units that have high PU cost, while generating a solution set that is made up of contiguous groups of planning units.

Running Marxan

As recommended by the CBC stakeholders, all marine targets were screened and stratified. Stratification is done to ensure that the conservation portfolio that is produced by Marxan is evenly scattered throughout the project area and sites are not clustered in one particular area. This process helps to build redundancy into the protected area network design, promoting resiliency in case future events may cause. We used the three marine ecoregions found in the Insular Caribbean to stratify the targets (Bahamian, Greater Antilles, and Lesser Antilles). Marine ecoregions represent ecologically strong cohesive units, sufficiently large to encompass ecological or life history processes for most sedentary species (Spalding et al. 2007).

Once the targets have been stratified, the next step was to set goals for each target to be used in Marxan. Goals can be set either as percentages or actual target abundance in area (e.g. hectares). There is a wide variety of ways in which goals can be set. Typically goals are set by expert committees, and revised as results are reviewed. For this exercise we investigated a “flat” goal of

20% for all targets. Since all of the raw Marxan input files are provided with this report, countries will have the ability to change goals (for example, using adaptive goal setting where rare targets have higher goals and vice-versa) and create their own scenarios and corresponding solutions. Table 7 lists some of the suggested edits to goal setting from the stakeholder's workshop and the associated response and/or resolutions that were taken.

Table 7. Suggested edits to goal setting and associated response and/or resolutions

GOALS	RESPONSE/RESOLUTION
It is unclear the procedure used to determine the conservation goals	For the Marxan model, we used flat goals of 10, 20 and 30% across all marine targets. We are also providing the users with all the Marxan input data so they will have the ability to choose and adjust their own goals and run their own model scenarios. We are providing the Marxan planning unit input file that includes both protected areas locked and not locked.
The goals assigned to the conservation targets are not stratified by region or coastal marine systems	In the revised model runs, all marine targets were stratified by marine ecoregion which have been scientifically delineated based on expert input and characterization of ecological integrity (Spalding et al., 2007)

Preparing Marxan Data

In order to run Marxan, we first had to create a planning unit file that had an attribute field containing a unique ID. To do this, we created a regular hexagon tessellation over the entire study area, each hexagons having a 500 square km area (slightly smaller than the gridded reef data that was used in the first step). Next, we assigned each hexagon planning unit to the reef unit that it intersected with. In cases where planning unit overlapped more than one reef it was assigned to the reef it intersected with the most by area. Finally, we used the planning unit file and the" all connections" file to create a comma delimited text file listing the strength of connections between planning units. We created this file in the same format as expected by Marxan as a bound.dat file (this file utilizes the BLM variable).

Before running Marxan, a particular scenario can use a "status" identifier that is used to "lock in" certain planning units, in other words, they are automatically "fixed" in the output solution. This is optional in Marxan but typically is a protected areas (or special interest area) layer. Planning units that are "locked in" are first considered when Marxan attempts to meet the conservation goals. If goals are met within these areas, no additional planning units are selected for that particular target goal. The status layer that was used in these scenarios was the latest version (2012) of the Caribbean Protected Areas database (for the Insular Caribbean) and for all other areas, the 2011 version of the World Database on Protected Areas. Table 8 lists some of the suggested edits to the status layer based on comments from the stakeholder's workshop and the associated response and/or resolutions that were taken. Figure 7 shows the general steps that were followed in the Marxan analysis (Schill and Raber, 2011).

Table 8 lists some of the suggested edits to goal setting from the stakeholder's workshop and the associated response and/or resolutions

PROTECTED AREAS	RESPONSE/RESOLUTION
All protected areas were treated the same. We need to separate protected areas out by IUCN category and treat them differently such as STRICT (I-IV) and LENIENT (V-VI)	Since the majority of the marine protected areas in the study area are not managed at all (>90%), it didn't make sense to separate out these two different management regimes within the protected areas. However, the IUCN category exists within the protected area GIS layer and countries can explore this type of analysis using the model output and GIS files provided.
Run Marxan with marine protected areas locked in	A suite of Marxan scenarios included the locking in of marine protected areas. See Appendix C for maps showing model output.

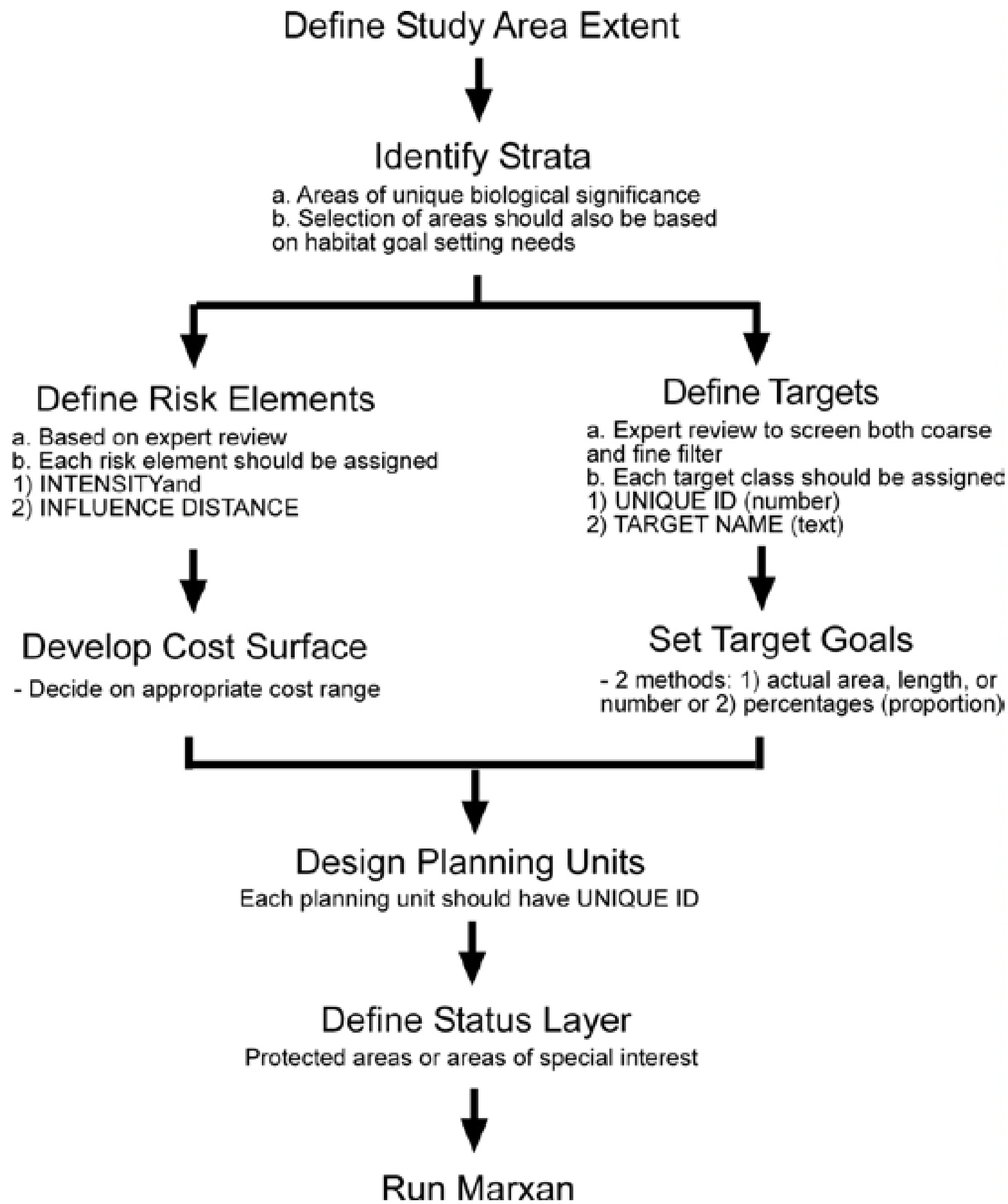


Figure 7. Suggested steps for preparing input data and conducting a Marxan analysis. The four basic data layers include conservation targets, risk elements that are used to create a cost (threat) surface, planning units, and status layer (protected areas) (Schill and Raber, 2011)

Running Marxan and Interpreting Output

Marxan analyses were completed for a) the larger area (Caribbean Basin and Gulf of Mexico) using only the coral reef targets and integrating the connectivity model output into the planning unit boundary file; and b) the smaller area (Insular Caribbean) using all the marine targets with no integration of connectivity information. For the first analysis (Caribbean Basin and Gulf of Mexico), four Marxan scenarios were chosen at the stakeholder workshop. The following scenarios were run with the coral reef targets set to a 20% goal:

1) Protected areas not locked in with cost (no connectivity modified BLM)

2) Protected areas locked in with cost (no connectivity modified BLM)

3) Protected areas not locked in with cost (with connectivity modified BLM)

4) Protected areas locked in with cost (with connectivity modified BLM)

Planning unit cost was computed using zonal statistics which calculated and assigned the mean value for each planning unit based on the threat raster model. We ran 100 repetitions at 1 million iterations each. The modified BLM scenarios took significantly longer time to run due to the additional computations. Results of these scenarios can be seen in map format in Appendix B and within the online map viewer listed below. The MVBEST output file that Marxan produces is listed as a table underneath each map scenario. This table shows you the results of the solution and if and by how much each target met the 20% goal.

In addition to the Caribbean Basin and Gulf of Mexico Marxan runs that calculated solutions on only the coral reef marine target, a separate Marxan analysis was conducted for the Insular Caribbean utilizing all other marine targets (as listed in the Marine Target section of this report). These targets were also stratified by marine ecoregion and all subsequent targets were set to a goal of 20%, using the same threat surface to calculate planning unit "cost". The following scenarios were chosen for this analysis:

1) Protected areas not locked in with cost

2) Protected areas locked in with cost

The output solutions for these runs are available in both the web viewer URL listed below or as maps in Appendix B. The MVBEST output file is listed as a table underneath each map scenario. It is important to note that these model runs have not included the modified BLM based on the marine connectivity calculations. As explained previously, all marine targets could not be included in the first Marxan run because not all targets were mapped consistently throughout the study area. However, the second round of Marxan runs included all targets because they had been consistently mapped throughout the Insular Caribbean. These maps can also be useful for identifying areas that meet conservation goals (e.g. 20%) in the most efficient way possible. For additional information on the Marxan algorithm, please refer to Ball et al. (2009).

Results of for each of the scenarios for the two analyses can be seen here:

http://www.arcgis.com/home/webmap/viewer.html?webmap=2cf302255c204805beb7e622547f086d&extent=-101.1621,-4.9888,-41.6602,36.2915

These maps can be expanded within the group layers by clicking on them in the table of contents and then viewing each individual layer. The outputs of these models and maps provide important decision support, highlighting areas that efficiently meet conservation goals and can be used as guidance for the marine protection planning process. These systematic decision support tools can be used to develop a set of regional management strategies that may include establishing new MPAs, protecting specific marine species, jointly managing trans-boundary ecosystems, or piloting ecosystem services and poverty alleviation projects. The ultimate goal is to seek agreement on a set of regionally important conservation areas, the threats that face them and the joint strategies needed to mitigate the threats and protect the important marine areas. In addition, the role of the Biological Corridor Steering Committee will be to identify specific follow-up steps for taking the project from plan to action.

Incorporation of GIS products into TNC's Caribbean Conservation Information System

All data and information products produced for this project have been incorporated into TNC's Caribbean Conservation Information System – a GIS and information database that was started in 2004 and contains the most comprehensive GIS database for the entire Caribbean. This database is widely known and accepted throughout the region and often the first source when requesting GIS data for this region. The database is organized at three scales:

a) Region – datasets are organized by both the Caribbean Basin and the Insular Caribbean
b) National – datasets at the country-level that have been organized for fifteen Caribbean countries typically gathered by in-country experts and government agencies.
c) Site/Local – sub-national datasets that were created/organized for specific project data.

TNC's information system encompasses two primary components: the first is a detailed database housing vast geospatial information layers about a) habitats and species (e.g. turtle breeding grounds, mangroves, and coral reefs); b) threats to habitats (e.g. tourism, pollution, fishing, and coastal development); and c) protected area boundaries and management information (http://maps.tnc.org/CARIBPA) and the second component is a suite of GIS-based tools designed to a) create "environmental risk surfaces" that indicate the level of threat to a particular habitat or species and are used to identify and assess protected area networks and conservation measures; b) identify critical areas of rare habitats across a landscape, and; c) facilitate the use of the site selection software Marxan to create optimal protected area scenarios based on quantitative conservation goals while minimizing impending threats to habitats.

All datasets produced for this project, as well as a vast majority of other GIS datasets housed in the information system are available for public distribution through TNC's Data Disclaimer and Distribution Agreement. A few of the datasets housed in the database have restricted distribution due to proprietary rights as requested by the owner. In these instances, the data requestor must contact the original owner to obtain access to these data. TNC will respect the decision of all parties involved and not distribute data without the consent of the data owner.

References

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Appendix A

MARINE TARGET DESCRIPTIONS and MAPPING DETAILS

(Adapted from Huggins et al., 2007)

Beaches

Beaches represent the lands bordering the sea - a place of natural beauty which humans use for recreation, inspiration, and commercial activities, ranging from tourism to sand mining. The beaches of the Caribbean receive millions of tourists from the northern hemisphere, often looking for a temporary get away from the rigorous winter of the higher latitudes. It is also home to a very specialized community of creatures that have adapted to live in this harsh environment. A transition zone between terrestrial and marine environments, the beach is a tough place to live because of ever-changing conditions. Submerged by seawater for part of the day and exposed to air for the other, often covered by sediments that may be moved to and from the beach at every breaking wave, the beach is a very dynamic habitat.

The strand line marks the highest place where the ocean washes the beach. The strand line is often marked by accumulated debris washed ashore by the ocean waves. This is an area rich with biological activity of the associated fauna. The strand line also marks a transition between the upper beach and the area of the beach that is within the range of tide. Different communities of organisms have adapted to different conditions of these zones. The upper beach is an area with primarily terrestrial characteristics, with species that use the ocean for part of their life cycles. Plant species such as the coconut palm (*Cocos nucifera*), the sea grape (*Coccoloba uvifera*), the beach morning glory (*Ipomea pes-caprae*) and the sea purslane (*Sesuvium portulacastrum*) provide cover for a number of animal species in the upper beach, such as the soldier crab (*Coenobita clypeatus*) and the willet (*Catoptrophorus semipalmatus*). During the summer through autumn months it is not unusual to find turtle hatchlings making their way from the nest, crafted by their mothers in the upper areas of many Caribbean beaches.

The inhabitants of the Intertidal zone, including crustaceans, such as the ghost crab (*Ocypode quadrata*), as well as mollusks and annelids that are preyed upon by wading birds like the least tern (*Sterna antillarum*) and the American oystercatcher (*Haematopus palliatus*), are adapted to part-time marine and part-time terrestrial living.

The seaward limit of land, which is exposed to air due to ebbing tidal flow, is referred to the low tide line mark. Below this line the land is continuously submerged in seawater, and is referred to as the sub-tidal zone. The community that inhabits this area includes fish species, such as the African pompano (*Alectis crinitus*), the permit (*Trachinotus falcatus*) and the yellowtail snapper (*Ocyurus chrysurus*), which are adapted to living in the marine environment full-time, by being well-suited to the shallow water, often crushed with strong wave action and coastal circulation.

Mapping Regional Distribution: Sandy beaches were mapped across the Caribbean Basin using archived high resolution (e.g. 1x1m) satellite imagery where available in one of three image libraries: ESRI World Imagery, Microsoft Bing Maps, and Google Maps. Imagery used for mapping were dated between 2006-2011 and came from a variety of sources including the IKONOS, GeoEye-1, Quickbird, and WorldView-2 satellite. Scenes were selected based on the level of cloud cover found in each of the image archives. Image analysts streamed the images over the internet using ERSI ArcGIS software, then employed on-screen digitization to delineate the beach features with 1-5 meter horizontal accuracy. Since beaches are easily recognizable features, the analysts succeeded in locating and capturing all Caribbean beaches to a high level accuracy. All archived images used in the analysis were previously orthorectifed, meaning they are geometrically correct void of any planimetric spatial errors.

Key Attributes 1) Sediment transport – beach size resulting from accretion and erosion, and influenced by proximity to rivers; 2) Natural disturbance – beach slope resulting from tidal action, coastal circulation, wave energy and wind.

Key Threats:1) Coastal development that affects and impacts ability of species to colonize the upper beaches, as well as coastal circulation and sediment transport; 2) Beach nourishment that alters the zonation of the beach with sediment from other areas; 3) Sand mining for construction that removes habitat; 4) Climate change that leads to altered circulation and sea level rise which could submerge the beach or affect sediment transport.

Coastal Mangroves / Wetlands

Coastal wetlands including mangrove forests are some of the most productive ecosystems in the world. Their high primary productivity and nutrient profusion make them essential to the breeding, foraging, and roosting of many species, including aquatic plants, fish, shellfish, insects, amphibians, birds, and mammals. By providing food, shelter, and protection from predators they serve their role of biological nurseries well. In addition, they reduce the amount of pollution flowing into the bays and ocean.

Mangroves occur across the entire Caribbean basin and generally consist of four principal mangrove species: *Rhizophorae mangle*, *Avicennia germinans*, *Laguncularia racemosa*, and *Conocarpus erecta.* Mangroves play an important functional role for many fish fauna, many of which spend their early juvenile life stages within this habitat. Mangrove leaf litter represents a major source of organic matter and nutrients to adjacent estuarine waters and is essential in supporting high productivity of many near shore waters.

Mangroves grow on a wide range of soil types, including heavy consolidated clays, unconsolidated silts, calcareous and mineral sands, coral rubble, and organic peats, with salinity concentration close to 35‰. The development of mangrove swamps is the result of: topography, substrate, freshwater hydrology, and tidal action. The hydrologic energy of riverine mangroves is high since it is dominated by river flow and tidal inundation. Fringe mangroves, on the other hand, are influenced mainly by frequent tidal inundation. Basin mangroves have even less hydrologic energy, because they are located inland of fringe or riverine communities, and as a result, are less frequently inundated by either tides or river floods.

Fish species composition and richness in any tropical mangrove system primarily depends upon: (a) its size and diversity of habitats together with its flood and tidal regimes; (b) its proximity to other mangrove systems, and (c) the nature of the offshore environment, particularly depth and current patterns. Proximity to other mangrove systems ensures colonization through movements of adults and juveniles, even by those species that have nonexistent or short larval duration. A corollary of this is that proximity to non-mangrove areas, such as coral reefs may influence fish species composition in the mangrove.

Mapping Regional Distribution: Mangroves were mapped across the Caribbean Basin using archived high resolution (e.g. 1x1m) satellite imagery where available in one of three image libraries: ESRI World Imagery, Microsoft Bing Maps, and Google Maps. Imagery used for mapping were dated between 2006-2011 and came from a variety of sources including the IKONOS, GeoEye-1, Quickbird, and WorldView-2 satellite. Scenes were selected based on the level of cloud cover found in each of the image archives. Image analysts were trained in how to recognize mangrove features based on texture and coastal context. Imagery was streamed over the internet using ERSI ArcGIS software, then the analysts employed on-screen digitization to delineate the mangrove features with 1-5 meter horizontal accuracy. All archived images used in the analysis were previously orthorectifed, meaning they are geometrically correct void of any planimetric spatial errors.

Key Attributes: 1) Vegetation type – area and percent cover of Mangrove forest species; 2) Community structure –population density of juvenile reef fish; 3) Seascape pattern and structure – combination of slope, elevation, and wave energy that characterize sheltered and low relief coastline that prevents uprooting; 4) Hydrological regime influenced by watershed dynamics – affecting sedimentation rates, freshwater flow, salinity, and nutrient loadings.

Key Threats: 1) Coastal development (dredging, filling) leads to habitat destruction, conversion, fragmentation, and increased erosion/sedimentation; 2) Logging/extraction of material from mangroves which leads to losses of key species of the ecosystem; 3) Incompatible operation of drainage or diversion systems/irrigation/flood control that modifies water levels and natural flow factors (freshwater inflow, saltwater flow); 4) Eutrophication, which lead to low oxygen conditions and increased algal blooms.

Estuaries

Estuaries are semi-enclosed, coastal areas in which the seawater is significantly diluted by freshwater coming from streams and rivers and groundwater that are feeding the estuary. The estuarine environment is a transition zone between the fresh water and seawater worlds. As such, the salinity within estuaries fluctuates frequently, creating stress on the organisms that inhabit these areas. Estuaries are considered as some of the most productive habitats on earth and also serve as important breeding and nursery areas for many marine species.

Estuaries are fascinating and beautiful ecosystems distinct from all other places on earth. The productivity and variety of estuarine habitats foster a wonderful abundance and diversity of wildlife. Many different habitat types are found in and around estuaries, including shallow open waters, freshwater and salt marshes, sandy beaches, mud and sand flats, rocky shores, oyster reefs, mangrove forests, river deltas, tidal pools, sea grass and kelp beds, and wooded swamps. The tidal, sheltered waters of estuaries support unique communities specially adapted for life at the margin of the sea, including: shore birds; fish, such as anchovies, bull sharks, sawfish, croaker, and lane snapper; crabs, and lobsters; marine mammals; clams, shrimp, and other shellfish; marine worms; sea birds; and reptiles. These animals are linked to one another and to an assortment of specialized plants and microscopic organisms through complex food webs and other interactions.

Mapping Regional Distribution: Areas of potential estuarine locations were first identified using discharge points of modeled streams of order 3 and higher using the Shuttle Rader Topography Mission (SRTM) 90m elevation data. In the Bahamas, where there are no known rivers due to the porous limestone geology, groundwater maps were used from the Bahamas Water and Sewage Department and a 2 km buffer was applied. Estuaries were mapped across the Caribbean Basin using archived high resolution (e.g. 1x1m) satellite imagery where available in one of three image libraries: ESRI World Imagery, Microsoft Bing Maps, and Google Maps. Imagery used for mapping were dated between 2006-2011 and came from a variety of sources including the IKONOS, GeoEye-1, Quickbird, and WorldView-2 satellite. Scenes were selected based on the level of cloud cover found in each of the image archives. Imagery was streamed over the internet using ERSI ArcGIS software, then the analysts employed on-screen digitization to delineate the estuarine features with 1-5 meter horizontal accuracy. All archived images used in the analysis were previously orthorectifed, meaning they are geometrically correct void of any planimetric spatial errors.

Key Attributes: Freshwater flow (base flow), seasonal freshwater pulsing (water levels), estuarine salinity – mixing of freshwater and sea water, tidal flushing, coastal geomorphology (embayments), depositional area for sediments, and nutrient input, water quality (visibility) are the main factors that characterize estuaries.

Key Threats: Estuaries are used, abused, and managed heavily for resource extraction, habitation and recreation (coastal development). The pressures on estuarine resources from population redistribution and growth are predicted to increase significantly in the next few decades. The resulting changes in nutrient loading (pollution) and hydrology (river dams affecting flow and volume) at the regional scale, as well as accelerated sea-level rise and climate change at a global scale, will lead to significant alterations of estuarine habitats.

Coastal Lagoons/Salt Ponds

Coastal lagoons are a unique type of estuarine system. They are usually semi-enclosed by land but have some degree of access to the open ocean. They are influenced by oceanic tides, precipitation, and freshwater runoff from land areas, evaporation, and wind. Their salinities can range from hyperhaline to oligohaline. Salt ponds fall under the category of hyperhaline lagoons. Anchialine ponds are landlocked saline bodies of water with permanent connections to the open ocean. The salinity in ponds may vary, ranging from polyhaline to euhaline; therefore do not fit the tradition definition of lacustrine (lakes) and palustrine (ponds) systems. Because these two categories could not be easily distinguished from the satellite imagery, they were lumped into one marine target.

Mapping Regional Distribution: Lagoons and salt ponds are widespread feature in the Caribbean region. These features were mapped across the Caribbean Basin using archived high resolution (e.g. 1x1m) satellite imagery where available in one of three image libraries: ESRI World Imagery, Microsoft Bing Maps, and Google Maps. Imagery used for mapping were dated between 2006-2011 and came from a variety of sources including the IKONOS, GeoEye-1, Quickbird, and WorldView-2 satellite. Scenes were selected based on the level of cloud cover found in each of the image archives. Image analysts were trained in how to recognize coastal lagoons and salt ponds features based on proximity to the shoreline, yet far enough to be only inundated occasionally by the ocean. Imagery was streamed over the internet using ERSI ArcGIS software, then the analysts employed on-screen digitization to delineate the coastal lagoon and salt pond features with 1-5 meter horizontal accuracy. All archived images used in the analysis were previously orthorectifed, meaning they are geometrically correct void of any planimetric spatial errors.

Key Attributes: Salinity – mixing of freshwater and sea water, tidal flushing, coastal geomorphology (embayments), depositional area for sediments, and nutrient input; salinity ranges between 30 and 5 ppt.

Key Threats : **Lagoons/Salt Ponds:** Similarly to estuaries, lagoons and salt ponds are used, abused, and managed heavily for resource extraction, habitation and recreation (coastal development). The pressures on estuarine resources from population redistribution and growth will increase significantly in the next few decades. Incompatible recreational activities; potential fresh water depletion; pollution due to incompatible resource extraction-mining/drilling. The resulting changes in nutrient loading (nutrification) and altered hydrology (river dams affecting flow and volume) effect lagoons at the regional scale. In addition, accelerated sea-level rise and climate change at the global scale, will lead to significant alterations of lagoons and salt pond habitats.

Seagrass

Seagrass communities are common throughout the waters of the Caribbean. They are home to a myriad of fish and invertebrates. Green sea turtles are regular inhabitants of these sunny expanses, using the areas to feed primarily on the aptly named “turtle grass”. Seagrass beds are primarily subtidal, with some extending into the intertidal zone. They are distributed throughout much of the near-shore areas, forming linkages to other marine communities through movement of animals and export of large quantities of slowly decaying organic matter. The seagrass beds provide habitat for diverse populations of macroalgae, epiphytic diatoms, invertebrates, and juvenile fish. Seagrass habitats serve a variety of functions, including: trophic support, refuge from predation, recruitment, provision of nursery areas, environmental filter, and waterfowl habitat.

These grass-dominated habitats are found in relatively clear, shallow water (~.5-10m). The substrate of these communities is comprised of carbonate sand and fine organic matter, which is a product of both autogenic (*in situ* production) and allogenic (trapping of suspended particles) processes. Seagrass beds in the Caribbean are characterized by the habitat-forming turtle grass (*Thalassia testudinum*), manatee grass (*Syringodium filiforme)*, shoalgrass (*Halodule spp.*), and calcareous green algae (*Halimeda spp.* and *Penicillus spp.*). Perhaps, most important of all, seagrasses act as “foundation species”, meaning that the persistence of the entire community rests on the persistence of seagrasses. Their loss from areas is associated with rapid declines of commercially and ecologically valuable species and overall community function. Essentially seagrasses, via their biogenic structure, ameliorate environmental stresses (e.g., biotic – predation; and abiotic – wave disturbance), that would otherwise lead to the local extinction of the great majority of associated flora and fauna.

Mapping Distribution: The regional maps were derived from a combination of data sources and were the same targets used in the 2007 Caribbean Ecoregional Assessment by The Nature Conservancy. Seagrass data from the Bahamas was mapped by the University of South Florida (Damaris Torres) using remote sensing analysis of 14 Landsat ETM images. Seagrass data from Puerto Rico and the Virgin Islands was extracted from NOAA habitat maps. Seagrass data from Cuba was digitized from maps produced as part of the National Marine Ecoregional Planning effort undertaken by WWF and colleagues from Cuba. Data from the remainder of the Caribbean was taken from World Conservation Monitoring Center seagrass dataset which was compiled from various sources. The final data represented medium to dense seagrass areas and was a combination of lines and polygons.

Key Attributes: 1) Community structure: species composition (i.e. Mollusks, crustaceans, echinoderms) and patch size; 2) Trophic structure (herbivore and predator densities); 3) Seascape pattern and structure: combination of substrate type (soft limestone rock or hard igneous rock communities), slope at the coastline and wave energy intensity; water clarity, nutrient dynamics, complex, temperature, sediment regime.

Key Threats: Habitat disturbance or destruction from boating and shipping activities, nutrient loading from sewage discharge and agricultural run-off, sedimentation from poor land development practices, industrial activities/discharge, and incompatible fishing.

Seabird Nesting Areas

Seabirds, shorebirds, herons, and numerous landbirds flock seasonally on winter foraging and nesting grounds of the Caribbean. Secluded cays and islets, rocky shores and cliffs, estuaries, lagoons and mudflats are some of the key habitats that provide attractive habitat for roosting and nesting in close proximity to the sea. Sooty terns (*Sterna fuscata*) nest in their hundreds of thousands on tiny off shore islands, traveling hundreds of miles to provision their chicks, and follow the ocean currents across the tropical Atlantic, as far as Africa for the rest of the year. Brown pelicans (*Pelicanus occidentalis*) and magnificent frigatebirds (*Fregata magnificens*) stay close to shore year round.

Most seabirds take advantage of small, isolated islands to nest in high densities. Absence of alien predators such as cats, rats and raccoons, suitable vegetation (or the lack of it) and proximity to feeding grounds, are some of the factors that contribute to suitable habitat for seabirds. A few ones, like the rare and endangered Black-capped Petrel (*Pterodroma hasitata)* travel further inland to nest in deep, forested cliffs of the interior of larger islands.

Herons and egrets prefer to nest in large mixed colonies close to water in the mangroves, while shorebirds are more likely to be found nesting on salinas and mudflats. Deep in the canopy of mangroves and coastal woodland Yellow Warblers (*Dendroica petechia*) and hummingbirds are joined by seasonal migrants—North American warblers like American redstarts (*Setophaga ruticilla*), on their way north to breed in the summer, followed by austral migrants, migrating from central and South America to breed in the Caribbean. Whatever the destination, the coastal wetlands of the Caribbean provide abundant food and shelter for birds on their wintering grounds or the ones just passing through.

Mapping Regional Distribution: Birds are probably one of the best studied groups of animals in the Caribbean, but with thousands of islands and many miles of inaccessible and remote beaches there are huge gaps in our knowledge of the distribution of species and habitats. The data used to represent seabird and shorebird nesting and roosting areas comes from an access database compiled over a 10 year period by William Mackin of The Society for the Study and Conservation of Caribbean Birds (SSCCB). These were the same marine targets used in the 2007 Caribbean Ecoregional Assessment by The Nature Conservancy. Locations were taken from published chapters in an upcoming book on Caribbean Sea birds, monitoring studies, and from local expert knowledge from SSCCB members. A total of 735 nesting and roosting point locations were identified and checked for spatial accuracy using Landsat ETM images or national topographic maps from each country. Species number, year of observation, and overall importance (ranked 0-2) were attributed to each point.

*Key Attribut*es: 1) Trophic structure: primary productivity (abundant food resources), and predator density (lower densities are better); 2) Vegetation type: species composition, vegetation height, density and structure or substrate type and exposure; 3) Connectivity among ecosystems: nesting site fidelity, proximity to feeding grounds.

Key Threats: Throughout the region, many of the nesting sites are threatened or are no longer suitable for nesting because of the presence of cats, rats, mongooses and raccoons. A few of these insatiable predators can extirpate a huge nesting colony. Meanwhile food resources are being reduced as pollution from coastal developments coupled with agricultural runoff affect coastal productivity. Pesticides and heavy metals accumulate in food chains. Over-hunting has become another threat to some of the once widespread bird species, such as flamingos or white-crowned pigeons. These factors combined place the shorelines and other coastal environments of the Caribbean among the most significant for wildlife as well as among the most threatened in the region.

West Indian Manatee

The West Indian Manatee occurs mainly around the Greater Antillean islands of Puerto Rico, Cuba, and to a lesser extent—Jamaica and Hispaniola. Centuries of hunting and alteration of habitat have greatly reduced their numbers. Although the Manatee historically occurred in the eastern Caribbean (Guadeloupe), it is no longer found there. Occasionally, Manatees are sighted in the Bahamas, but these are thought to come from Florida, and at present there is not a year round resident population in the Bahamas.

Mapping Regional Distribution: Critical manatee areas were mapped as point data through merging datasets from a variety of sources. These include National monitoring datasets from Jamaica (NEPA) and the Dominican Republic (expert input), Puerto Rico (USFWS sightings data based on aerial surveys), Manatee data for other areas was compiled from on-line sources. A total of 118 point locations were identified as critical manatee areas for the three marine ecoregions. To identify shelf areas (0-200 m) that were of more or less importance to other marine mammals, we used 123 sightings representing 15 cetacean species from the Ocean Biogeographic Information (OBIS) database for the insular Caribbean. Individual sights were attributed to the nearest coastal shelf unit (total of 63 for the Caribbean). Coastal shelf units were then ranked from 1-3 (1=low; 2=medium; 3= important) based on the number of sightings. Fifteen shelf units were classified as important, 14 as medium and 34 as low. These were the same marine targets used in the 2007 Caribbean Ecoregional Assessment by The Nature Conservancy.

Key Attributes: 1) Population structure and recruitment: abundance and age distribution of animals, their reproductive success; 2) Water acoustic regimen, as measured by noise levels; 3) Connectivity among ecosystems: oceanographic processes that reflect the notorious long distance migration patterns (can be monitored by visitation densities at known calving and feeding grounds);4) Seascape pattern and structure: combination of coastal geomorphology, narrow continental shelves, oceanographic dynamics.

Key Threats: 1) Shipping activities: collisions can cause injury and mortality; 2) Fishing (gear, incidental take): causes injuries and mortality; 3) Acoustic disturbances; 4) Industrial discharge that degrades habitat.

Reef Fish Spawning Aggregations

Reef fish generally live in solitary or small groups, although some species exhibit schooling behavior. When larger numbers of reef fish are observed, these aggregations usually form for feeding, shelter or spawning. By definition, a spawning aggregation is a group of non-specific individuals grouped together in densities three times higher than those found in non-reproductive periods. Aggregations can also be recognized by indirect evidence such as swollen abdomens, spawning colorations or behaviors, and by direct evidence, such as observation of hydrated eggs or actual spawning activities. Reef fish spawning aggregations occur in tightly defined locations and at predictable times, making them very vulnerable to overfishing. Reef fish spawning aggregations are one of the most dramatic and important events in the life history of reefs. At times, tens of thousands of individuals aggregate and spawn en masse, releasing gamete clouds so dense that they obscure all vision within Caribbean waters, famous for their turquoise translucence. The density of the spawning adults attracts predators, such as sharks and dolphins, while the high density egg release attracts planctivorous organisms including whale sharks.

Two different types of spawning aggregations have been defined, "resident" and "transient", using the following three criteria: the frequency of aggregations, the longevity of aggregations, and the distance traveled by fish to the aggregation. Spawning in resident aggregations is common to most rabbitfish (iguanids), wrasses (labroids) and angelfish (cantharides). Resident spawning aggregations are brief (1-2 hours) and frequent (often daily), and involve short travel distances. By contrast, most grouper (errands), snapper (litanies), jacks (carangids), along with several other families, form transient spawning aggregations. Transient aggregations generally exhibit the following characteristics: a) fish frequently migrate long distances (can be > 100 km) to the aggregation site, sometimes using specific routes; b) aggregations typically form for only a few months of the year; c) the formation of aggregations is entrained to the lunar cycle; d) the duration of the aggregation is from a few days to a few weeks each lunar cycle; e) aggregations occur during a limited period or season of the year, possibly in relation to day length or seawater temperature. For the species that use this strategy, it appears that all reproductive activity for the year takes place within these aggregations, as there is no evidence of spawning in these species outside the aggregation.

Many sites that serve as spawning aggregation sites for one transient spawning species appear to serve as multi-species spawning aggregation sites, at predictable times and locations. These sites are all windward, facing reef promontories that jut into deep oceanic waters. Reef promontories have been shown to harbor multi-species reef fish spawning aggregations in Belize, the Cayman Islands, Cuba, and Mexico and the pattern may be more wide spread.

Reef fish spawning aggregations are highly vulnerable to fishing. For example, Nassau grouper, *E. striatus*' aggregations, have been extirpated in: Belize, the Bahamas, Honduras, Mexico, Virgin Islands, Bermuda, Puerto Rico, Dominican Republic, and Florida. In part, a result of this overfishing at their spawning sites, they are listed as "endangered" by the IUCN. Other grouper species appear to be showing similar declines. These trends are common throughout the Caribbean, where many known grouper spawning aggregations have been fished to near extinction.

Mapping Regional Distribution: The locations of reef fish spawning aggregations were compiled from a variety of sources including local fishermen in each country, published literature, and expert input from the Society for the Conservation of Reef Fish Spawning Aggregations (SCRFA) and Dr. Brian Luckhurst. All known spawning areas were associated with species and approximate number (if known) and geo-referenced. A total of 100 transient spawning areas representing twelve species were mapped within the insular Caribbean ecoregions. These were ranked from 1 to 3 based on the source of the data and confidence in the reported location. In addition to known aggregation sites, a predictive model was created to identify areas along the shelf with suitable geomorphic characteristics (promontories, large adjacent reef area). These areas were used to represent potential historic aggregation sites which are no longer active today. A total of 750 10 km shelf segments (30 meter bathymetric contour) were identified based on shelf morphology.

These were the same marine targets used in the 2007 Caribbean Ecoregional Assessment by The Nature Conservancy.

Key Attributes: 1) Population structure and recruitment: SPGS play a crucial role in the life cycle of fish populations. The health of the population is a function of the densities and structure of key species at different life stages (adult and eggs and larvae). This key attribute can be monitored from fish length (median size vs. minimum size at reproduction) or from size frequency distribution of each of several key species, e.g. Nassau, Black Groupers, Mutton snappers, Cubera snappers, with the minimum size at their reproductive maturity; 2) Seascape pattern and structure: combination of reef geomorphology (shape, slope), water temperature, current speed and direction at surface and aggregation depth (25 - 35 m), and tide state; 3) Connectivity among ecosystems: connectivity with migration routes, larval dispersal and nursery areas measured by species densities.

Key Threats: Overfishing is the clearest and the largest threat to reef fish spawning aggregations as it alters population structure and recruitment, a key attribute of this target. These aggregations form during predictable times, in known locations, and can be very vulnerable, particularly to net or trap fishing. Handline fishing, though lighter in pressure, has been known to extirpate spawning aggregation sites for Nassau grouper. The Live Reef fish Food Trade, largely feeding the high demand in Hong Kong has created extreme pressures on spawning aggregations throughout the Indo-Western Pacific and appears to be spreading into Caribbean Waters. This threat accelerates the existing threat of overfishing from local subsistence or small-scale commercial fishers within the region. Spawning aggregation sites can also be threatened by decreasing water quality with inputs from riverine sediments, pollutants, and/or fresh water.

Coral Reefs

Coral Reefs are the most famous hard bottom habitats in the Caribbean. The hard bottom habitats are usually found in areas where there is a strong circulation that carries away finer sediment. The organisms that inhabit this environment have special adaptations to anchor themselves to the bottom of the ocean to avoid being carried away. We decided not to focus on other types of hard bottom habitats other than coral reefs since their remote identification is difficult, and mapping these complexes has had very little attention in the past.

Coral reefs are an extremely important member of the Caribbean marine ecosystem because they create three-dimensional structures that provide home to a large array of organisms. Coral species are remarkably evenly distributed around the Caribbean. In almost all reefs six scleractinian genera (Acropora, Montastrea, Porites, Diploria, Siderastrea, and Agaricia) and one hydrozoan (Millepora) constitute over 90% of the total coral biomass. However, studies suggest that relative species dominance does vary geographically within the Caribbean. Coral reefs occur in many shapes and forms, and have been divided into three basic types: fringing reefs that form barriers along the shore; barrier reefs that are separated from the coast by a large lagoon or a channel; and atolls, which resemble a chain of corals surrounding an island. For our mapping purposes, we have divided corals reefs into: shallow reef (0 to 5 meters), fore reef (5 to 30 meters), and biogenic reef formed islands.

Mapping regional distribution: The coral reefs were mapped as part of the Millennium Reef Mapping Project led by Dr. Serge Andréfouët from the University of South Florida (Andréfouët et al., 2005). The shelf areas of all Caribbean islands were classified from Landsat ETM images using a global 4-tiered classification scheme.

Reef and shelves were classified based on geomorphology not biotic cover. A total of 126 classes were identified for the three Caribbean marine ecoregions. These classes were then simplified into a shallow and fore reef classes by lumping together selected classes that represented true coral reef structures (as opposed to hard-bottom, sand, or seagrasses). The data were checked against expert opinion and selected field investigations in Jamaica, Grenada, Bahamas, and Mexico but a quantitative accuracy assessment was not undertaken. These were the same marine targets used in the 2007 Caribbean Ecoregional Assessment by The Nature Conservancy.

Key Attributes: 1) Population structure and recruitment, measured by percent cover of live coral on reef; 2) Herbivory, an important process to prevent algae taking over the reef, measured through the population density of herbivores; 3) Water quality and clarity, measured by nutrient loading and turbidity respectively; 4) Climatic processes which affect sea level rise, temperature and wave energy.

Key Threats 1) Fishing & harvesting aquatic resources which leads to resource depletion and disruption of trophic structure (reduced species diversity, specifically loss of herbivory); 2) Destructive fishing (trawls, nets, traps) which causes habitat loss; 3) Climate change which induces bleaching-mortality and diseases and leads to a loss of live cover on reef; 4) Coastal development (shoreline stabilization, land reclamation and sewage discharge) which leads to habitat destruction, increased erosion/sedimentation, nutrient loading and discharges of toxins/contaminants.

Rocky Shores

Rocky shores dominate much of the Caribbean coastline and are colonized by a wide variety of marine algae and animals that are adapted to very stressful environments. These organisms have to tolerate wide variations in: desiccation, temperature, salinity, wave activity, food availability, and predation pressure, in order to survive and reproduce. The adaptations of these organisms are evident in the distinct vertical zonation of rocky intertidal communities. Rocky intertidal communities are found on both— limestone and volcanic rock hard-substrate shorelines region-wide.

The upper and lower boundaries of these communities are set by the low and high tide lines, which in the Caribbean range from 6 to 15 inches in vertical elevation. Tropical rocky intertidal systems are characterized by three distinct elevation zones: a white/upper intertidal zone, a black/mid-intertidal zone, and a yellow/lower intertidal zone. The upper, white zone is flooded only once a month on spring high tides and is barren of most plant life. The mid-zone, black intertidal area, is flooded approximately 50% of the time over a lunar cycle (~28 days) and gains its characteristic dark coloration from encrusting, desiccant resistant marine algae. The lower, yellow zone is flooded daily and again gains its coloration from marine algae, which blanket the entire rock surface. The algal community in this area is much more diverse and foliose in structure, with representative species from subtidal algal assemblages and alga which are strictly intertidal.

Intertidal zones are home to a diverse assemblage of invertebrate grazers and predators unique to these communities. Nerite and periwinkle snails, that are highly tolerant to extreme conditions, inhabit the upper-white and mid-black zone, while a much more diverse assemblage of gastropod grazers (Nerites – 6 species, Turbans – 3 species), gastropod predators (Muricids – 4 species), urchins, chitons, mussels, barnacles, annelids, sea cucumbers, tunicates, sponges, crabs, and amphipods occupy the lower yellow zone. Rocky shores are important feeding grounds for puffer and trigger fish, as well as generalist wrasse feeders and herbivorous fish (e.g. princess parrot fish).

Mapping Regional Distribution: Rocky Shores were mapped across the Caribbean Basin using archived high resolution (e.g. 1x1m) satellite imagery where available in one of three image libraries: ESRI World Imagery, Microsoft Bing Maps, and Google Maps. Imagery used for mapping were dated between 2006-2011 and came from a variety of sources including the IKONOS, GeoEye-1, Quickbird, and WorldView-2 satellite. Scenes were selected based on the level of cloud cover found in each of the image archives. Image analysts were trained in how to recognize rocky shores features based on texture and coastal context. A coastal slope analysis based on the most accurate elevation data available, helped guide the analysts to the areas where rocky shores were more likely to exist (areas of steeper slope). Imagery was streamed over the internet using ERSI ArcGIS software, then the analysts employed on-screen digitization to delineate the mangrove features with 1-5 meter horizontal accuracy. All archived images used in the analysis were previously orthorectifed, meaning they are geometrically correct void of any planimetric spatial errors.

Key Attributes: Community structure: 1) Species composition (i.e. Mollusks, crustaceans, echinoderms); 2) Trophic structure – herbivore and predator densities; 3) Seascape pattern and structure: combination of substrate type (soft limestone rock or hard igneous rock communities) and substrate availability slope at the coastline and wave energy intensity.

Key Threats: 1) Fishing: resource depletion and alteration in predation regime reduce species diversity; 2) Coastal development, including shoreline stabilization, land reclamation, habitat destruction, and sewage discharge, cause nutrient loading and reduce species diversity.

MARINE CONSERVATION TARGETS AND AREA FOR THE INSULAR CARIBBEAN

ECOREGION	ID	Hectares	Sq Km
Bahamian	10	114,801,897	1,148,019
Eastern Caribbean	20	92,748,469	927,485
Greater Antilles	30	143,447,761	1,434,478
		350,998,127	**3,509,981**

MARINE TARGET	ID	Hectares	Sq Km
Bahamian Coral Reef	1012	291,067	2,911
Eastern Caribbean Coral Reef	2012	92,014	920
Greater Antilles Coral Reef	3012	462,129	4,621
		845,210	**8,452**
Bahamian Sandy Beach	1017	9,230	92
Eastern Caribbean Sandy Beach	2017	1,797	18
Greater Antilles Sandy Beach	3017	9,128	91
		20,154	**202**
Bahamian Estuary	1013	2,984	30
Eastern Caribbean Estuary	2013	368	4
Greater Antilles Estuary	3013	88,314	883
		91,666	**917**

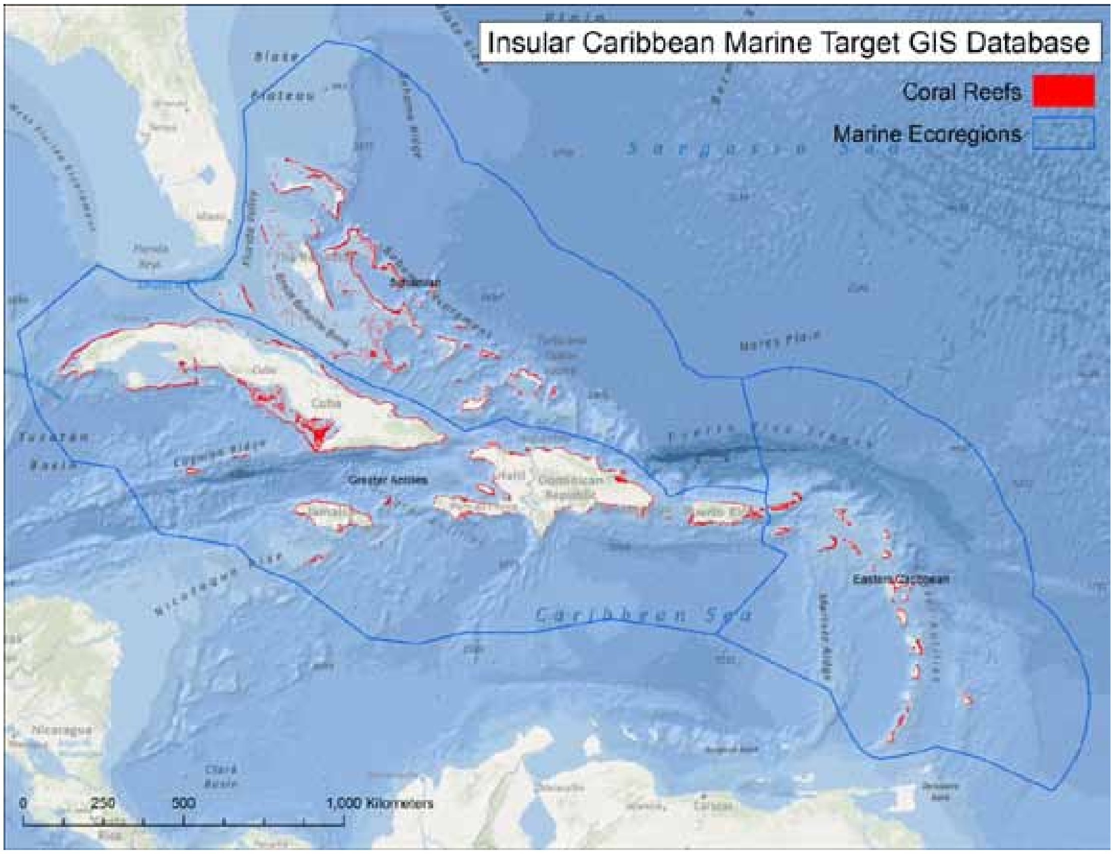
Bahamian Coastal Lagoon	1010	17,044	170	
Eastern Caribbean Coastal Lagoon	2010	5,172	52	
Greater Antilles Coastal Lagoon	3010	39,378	394	
		61,594	**616**	
Bahamian Manatee	1014	8	0.08	
Greater Antilles Manatee	3014	139	1.39	
		147	**1.47**	
Bahamian Mangrove	1015	153,947	1,539	
Eastern Caribbean Mangrove	2015	6,882	69	
Greater Antilles Mangrove	3015	938,917	9,389	
		1,099,745	**10,997**	
Bahamian Rocky Shore	1016	159,636	1,596	
Eastern Caribbean Rocky Shore	2016	686,006	6,860	
Greater Antilles Rocky Shore	3016	2,285,059	22,851	
		3,130,702	**31,307**	Kilometers
Bahamian Seabird Nesting Area	1018	10	0.10	
Eastern Caribbean Seabird Nesting Area	2018	7	0.07	
Greater Antilles Seabird Nesting Area	3018	7	0.07	
		25	**0.25**	
Bahamian Seagrass	1019	5,491,302	54,913	
Eastern Caribbean Seagrass	2019	276,893	2,769	
Greater Antilles Seagrass	3019	2,997,601	29,976	
		8,765,796	**87,658**	
Bahamian SPAGS High	1022	43	0.43	
Bahamian SPAGS Low	1020	163	2	
Bahamian SPAGS Medium	1021	327	3	
Eastern Caribbean SPAGS High	2022	135	1	
Eastern Caribbean SPAGS Medium	2021	54	1	
Greater Antilles SPAGS High	3022	246	2	
Greater Antilles SPAGS Low	3020	506	5	
Greater Antilles SPAGS Medium	3021	351	4	
		1,826	**18**	

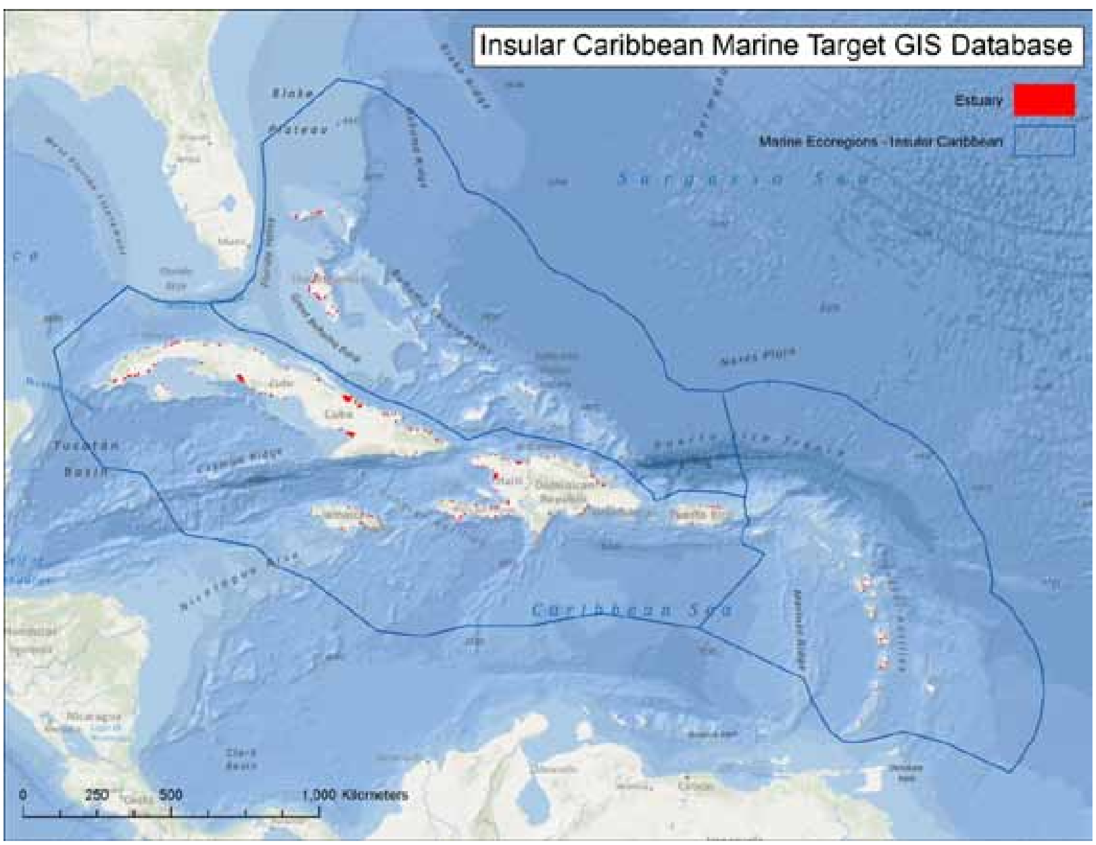
APPENDIX B

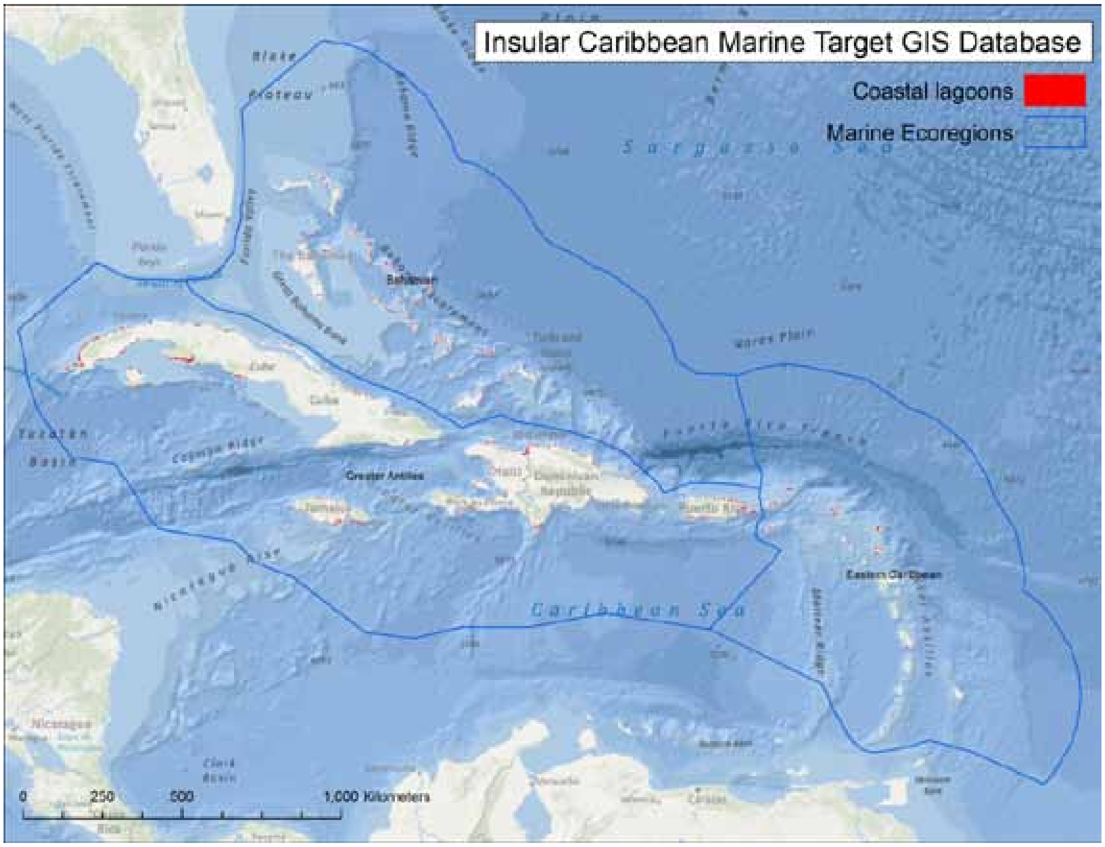
Maps and Graphs

1. **Marine Conservation Targets**
2. **Marine Threat Models**
3. **Marine Protected Areas**
4. **Marine Marxan Scenarios**
5. **Marine Connectivity Graphs**

MARINE TARGETS



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Coastal lagoons
Marine Ecoregions
Bahamian
Greater Antilles
Eastern Caribbean
Caribbean Sea
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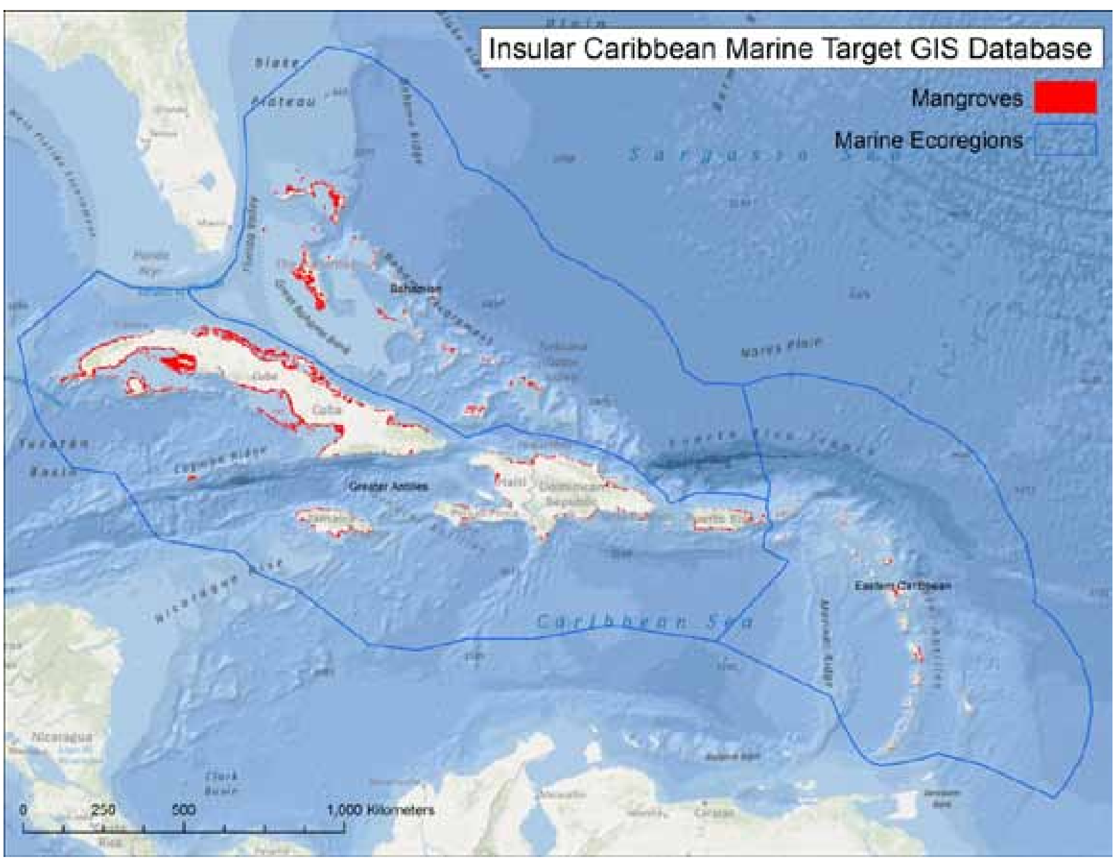
Insular Caribbean Marine Target GIS Database
Mangroves
Marine Ecoregions
Bahamian
Greater Antilles
Eastern Caribbean
Caribbean Sea
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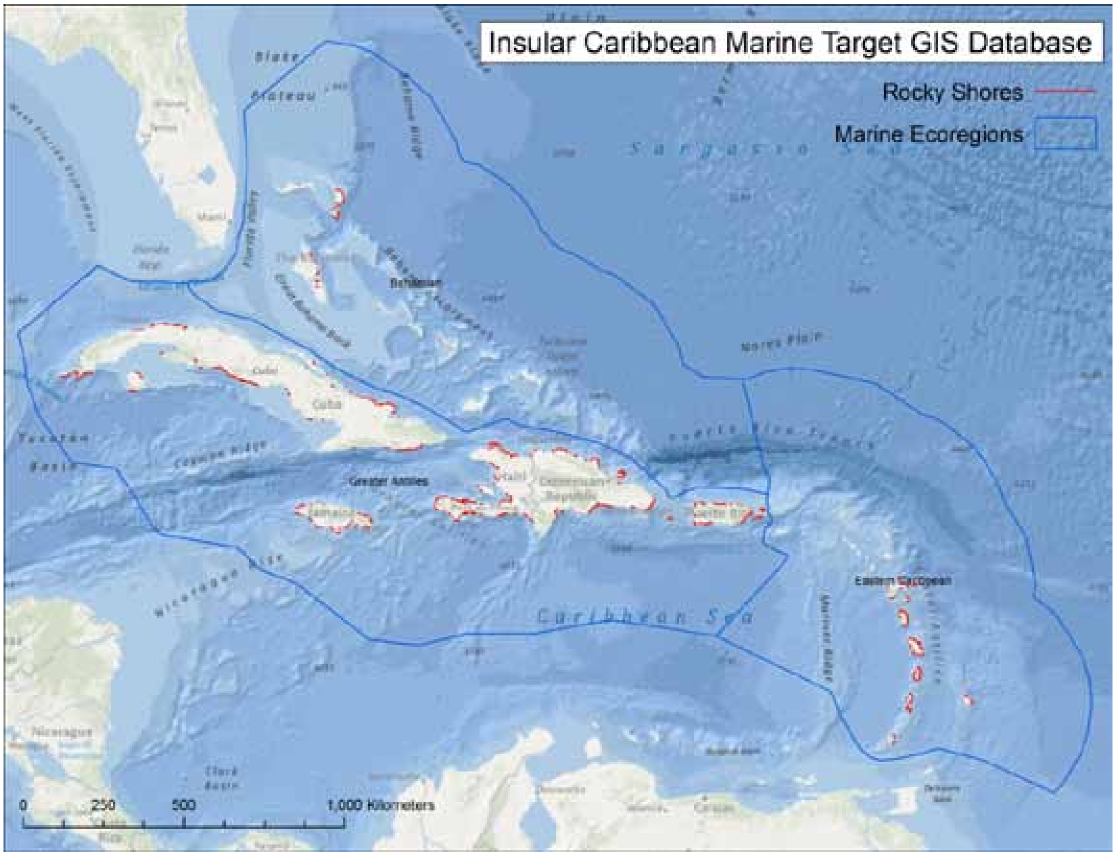
Insular Caribbean Marine Target GIS Database
Rocky Shores
Marine Ecoregions
Sargasso Sea
Bahamian
Greater Antilles
Eastern Caribbean
Caribbean Sea
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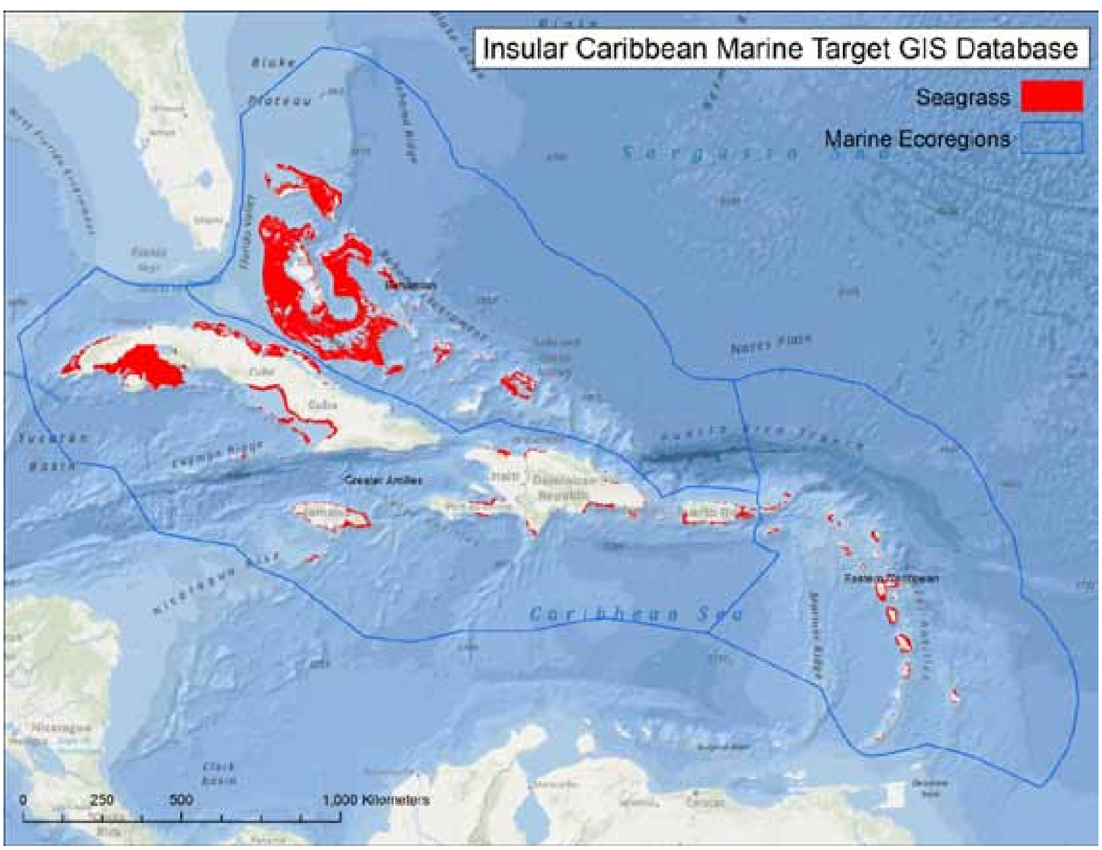
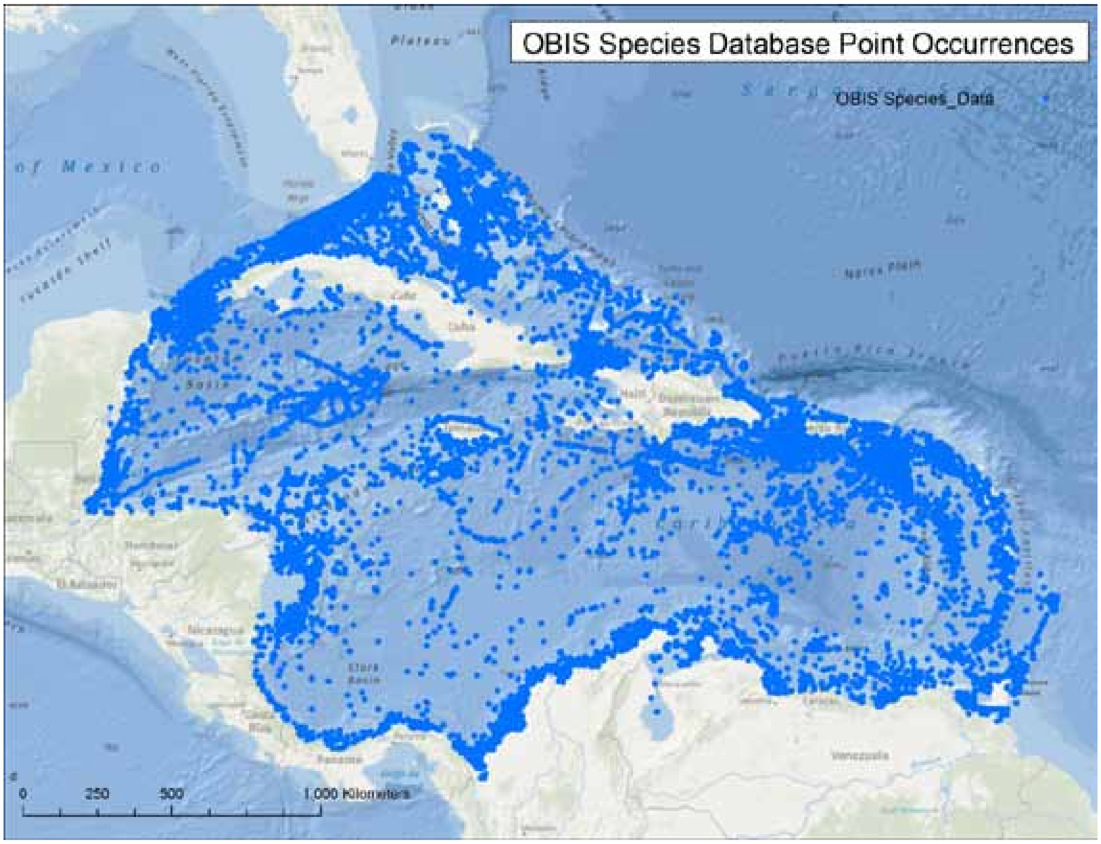
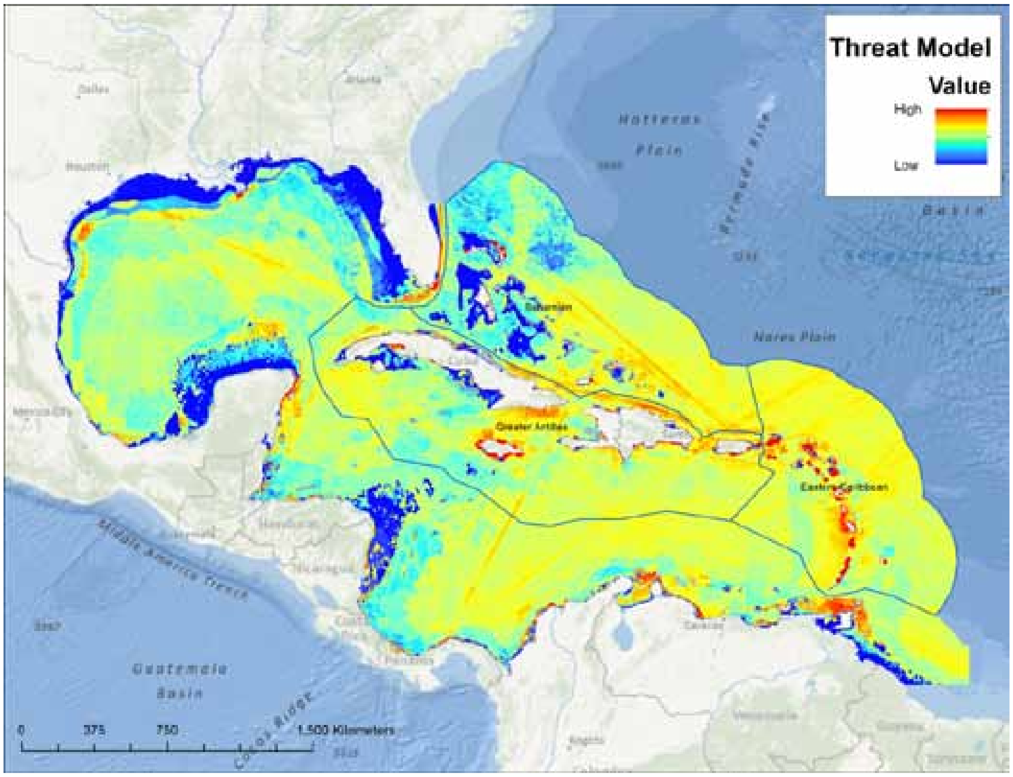
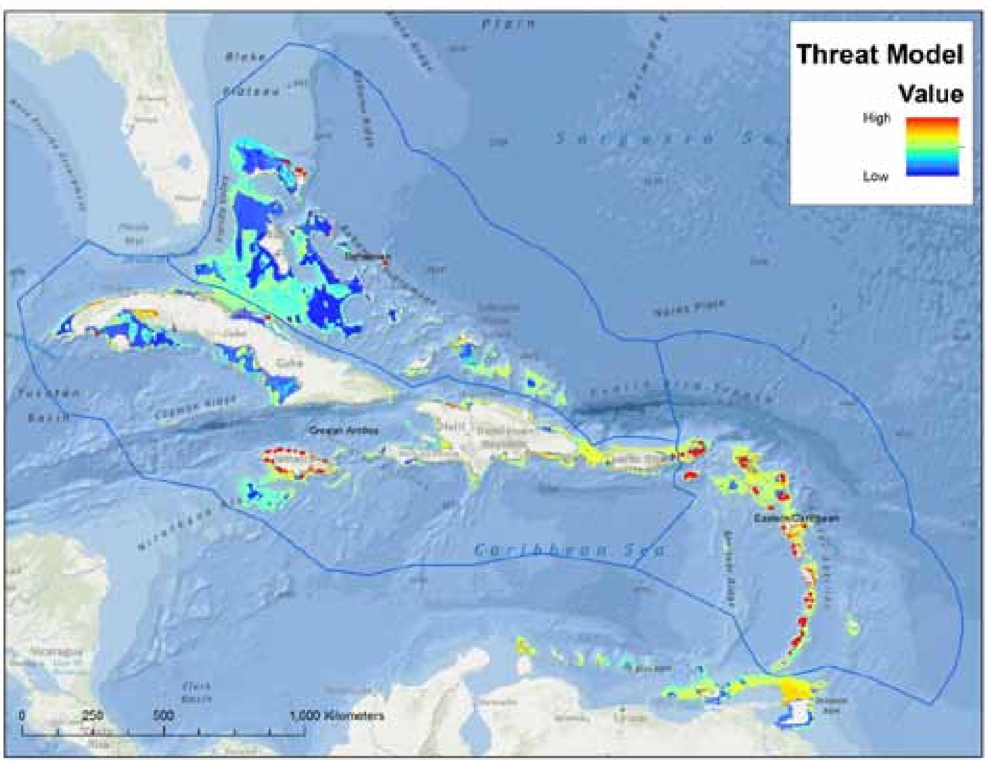

Insular Caribbean Marine Target GIS Database
Seagrass
Marine Ecoregions
Sargasso Sea
Bahamian
Greater Antilles
Eastern Caribbean
Caribbean Sea
0 250 500 1,000 Kilometers


OBIS Species Database Point Occurrences
OBIS Species_Data
0
250
500
1,000 Kilometers

MARINE THREATS

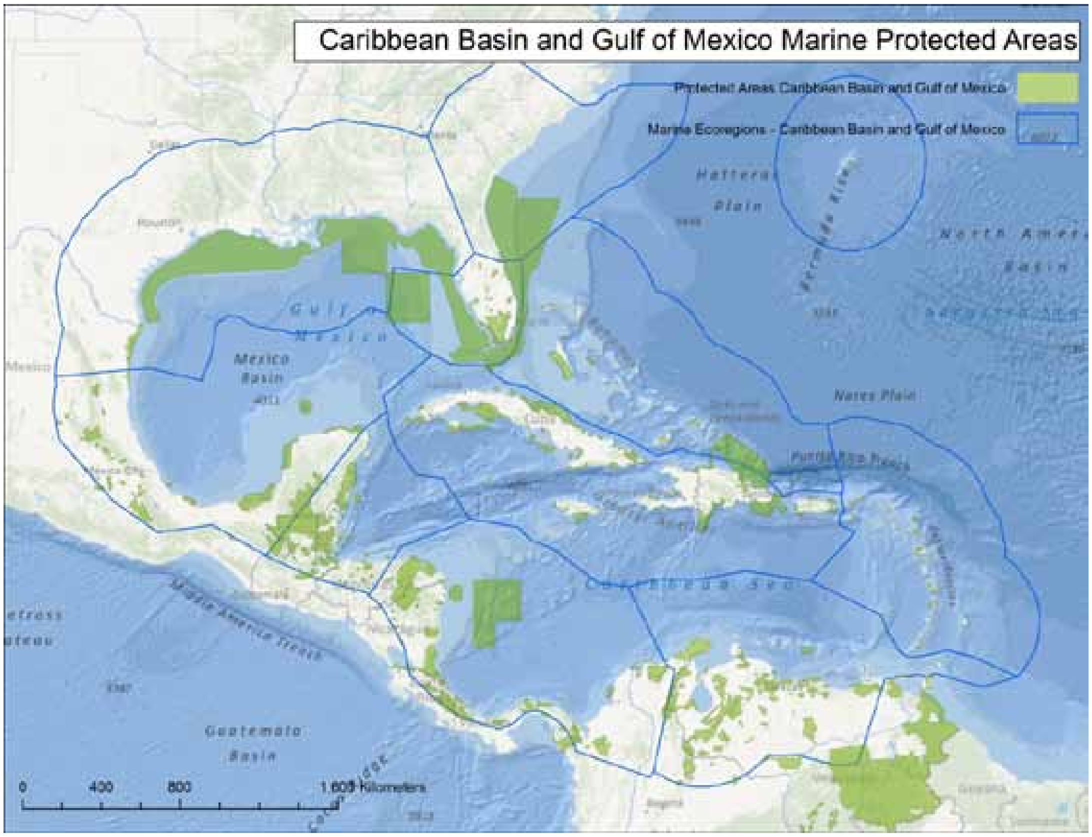


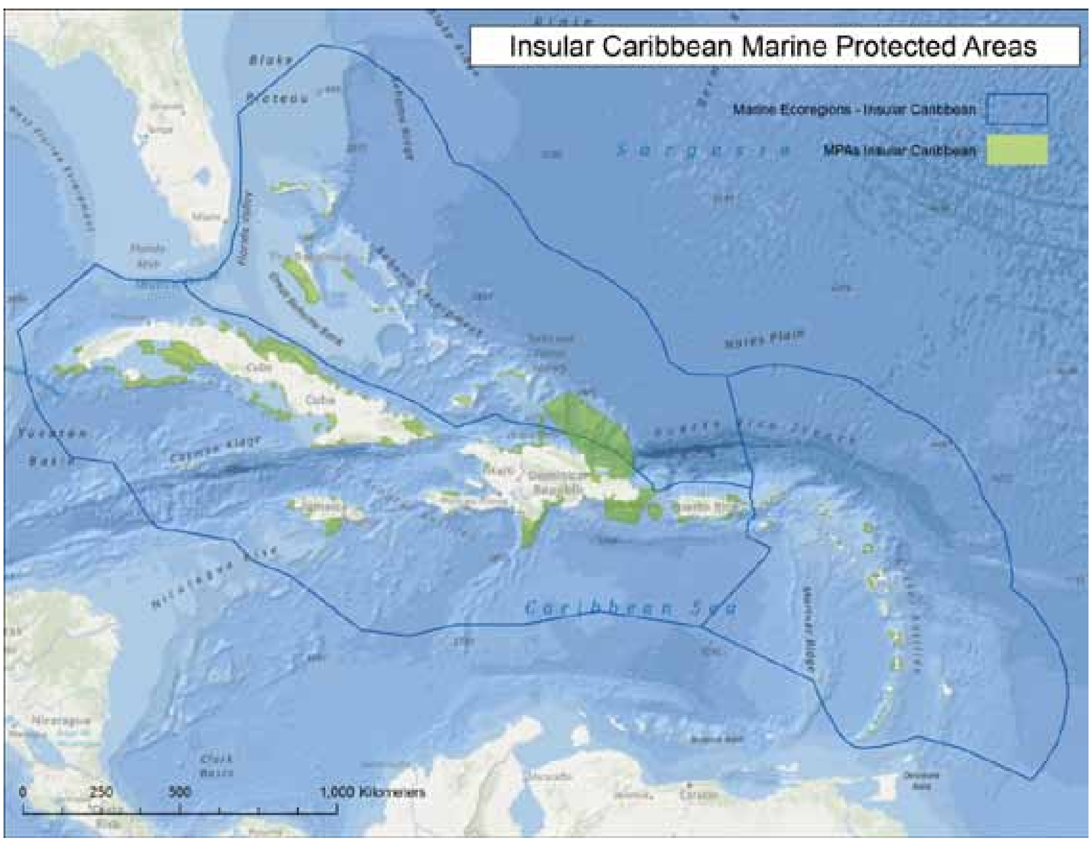
Marine threat model – Caribbean Basin and Gulf of Mexico



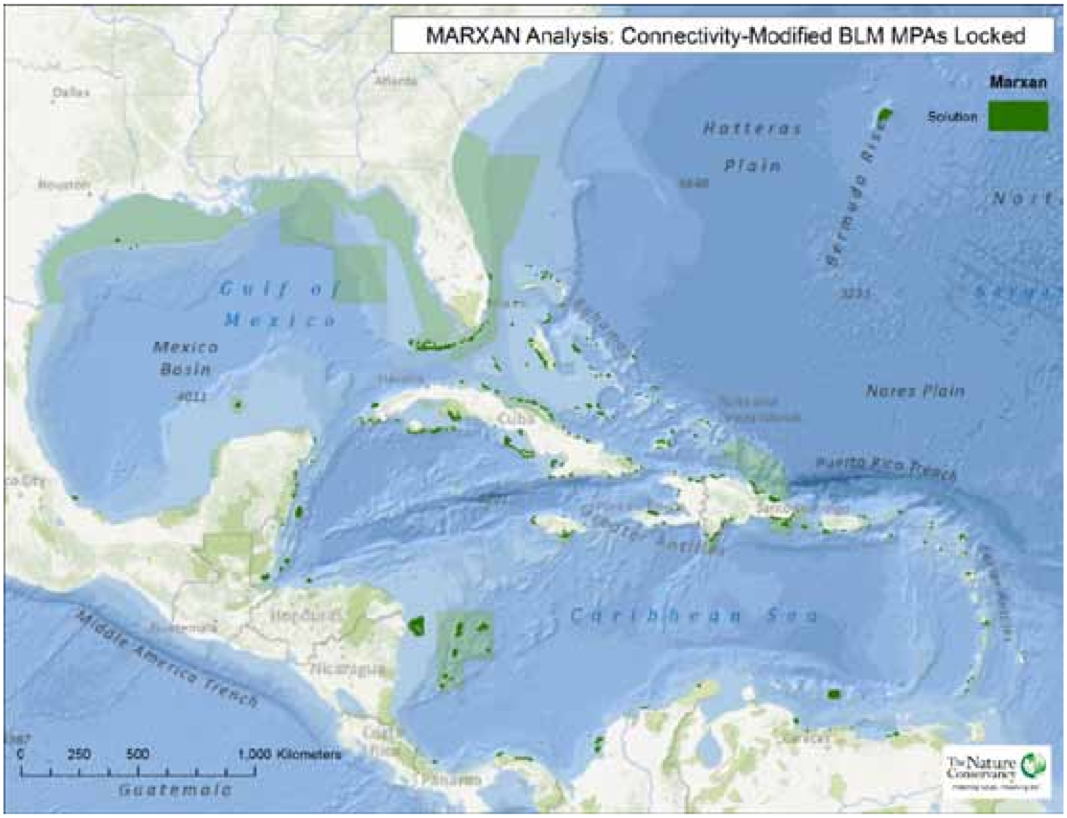
Marine threat model – Insular Caribbean

MARINE PROTECTED AREAS

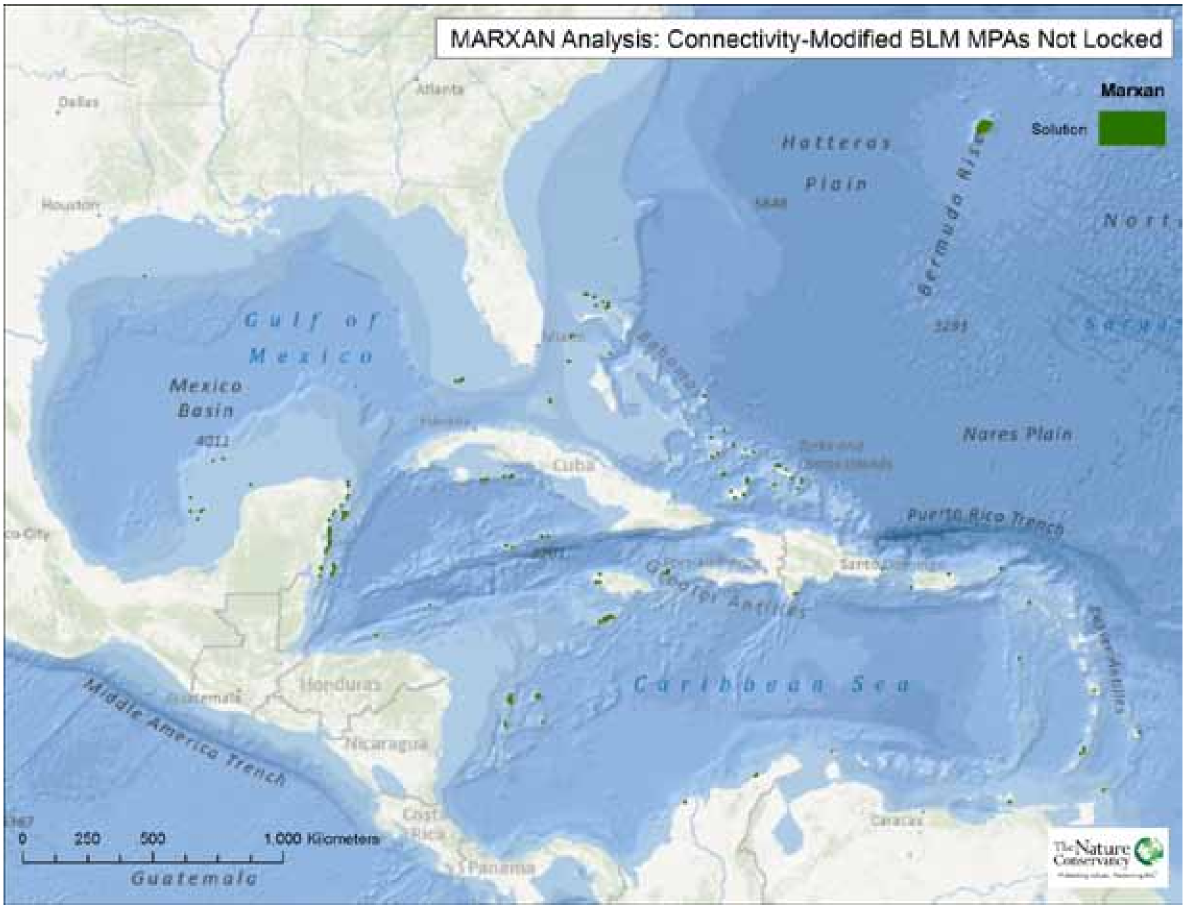




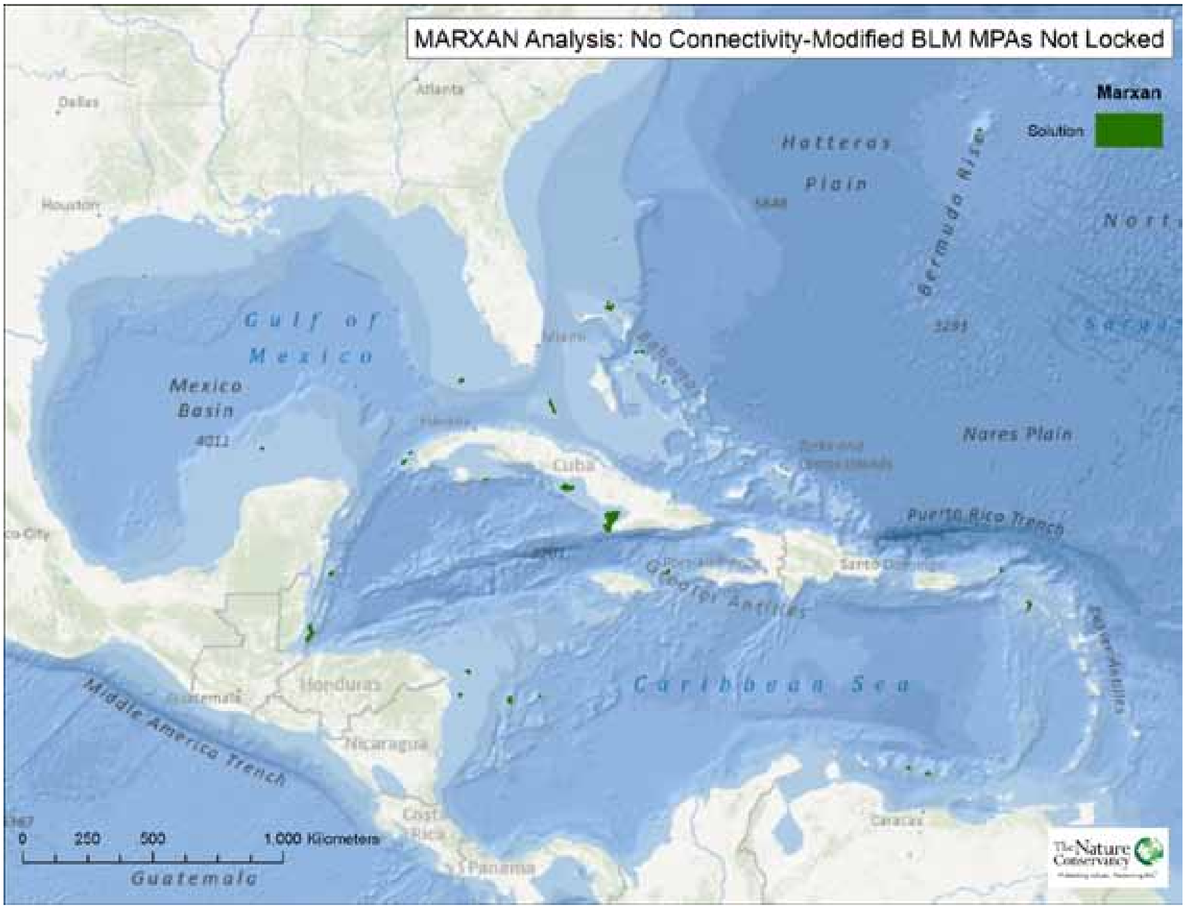
MARINE MARXAN SCENARIOS



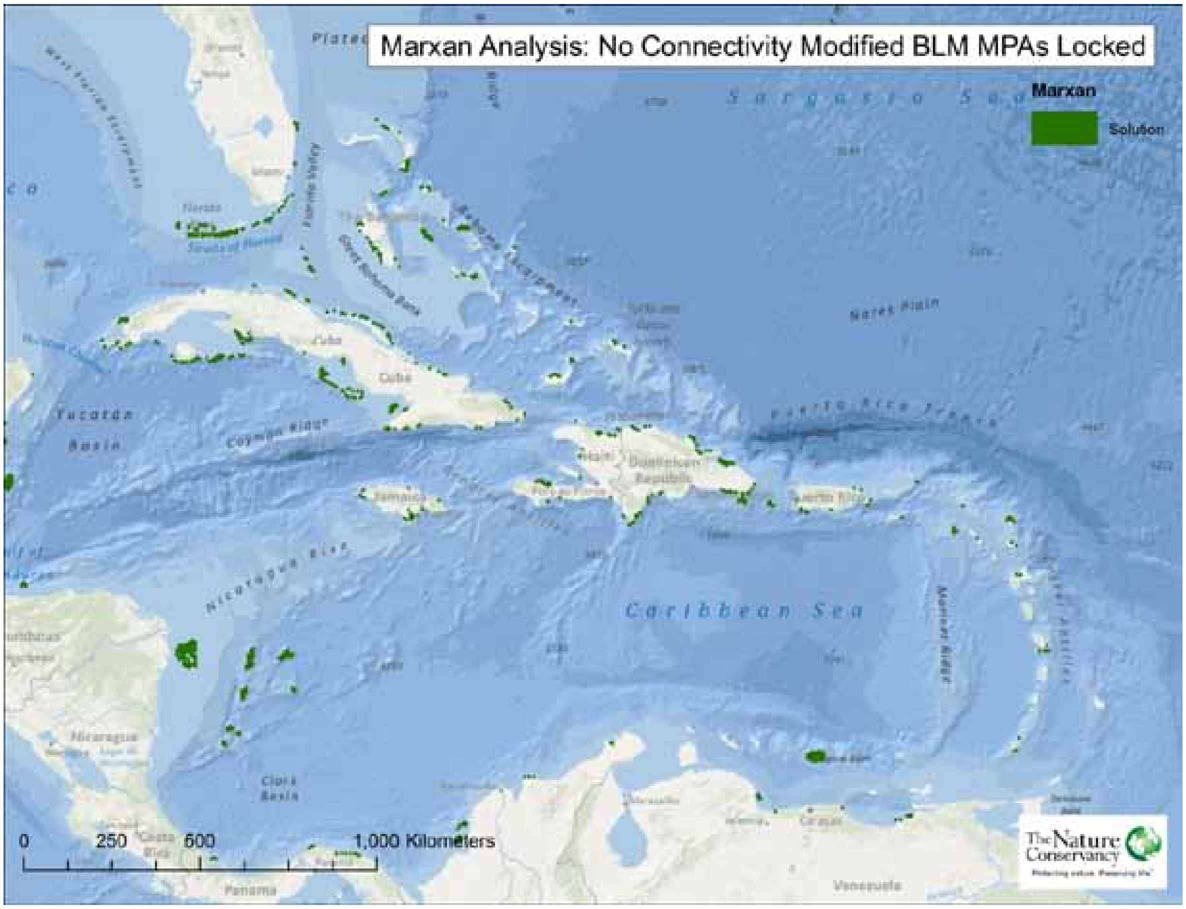
Conservation Feature	Feature Name	Target	Amount Held	Occurrences Held	Separation Target	Target Met
68	Western Caribbean	35379.852	176899.26	386	0	yes
67	Southwestern Caribbean	48944.248	53503.49	157	0	yes
69	Southern Gulf of Mexico	9041.096	9460.66	31	0	yes
66	Southern Caribbean	10927.96	47295.71	166	0	yes
43	Northern Gulf of Mexico	4355.718	2435.72	1	0	no
65	Greater Antilles	92425.826	92402.62	236	0	yes
70	Floridian	18201.036	15938.03	4	0	no
64	Eastern Caribbean	18402.834	18403.11	76	0	yes
62	Bermuda	14795.76	14022.93	3	0	no
63	Bahamian	58213.472	58176.06	187	0	yes



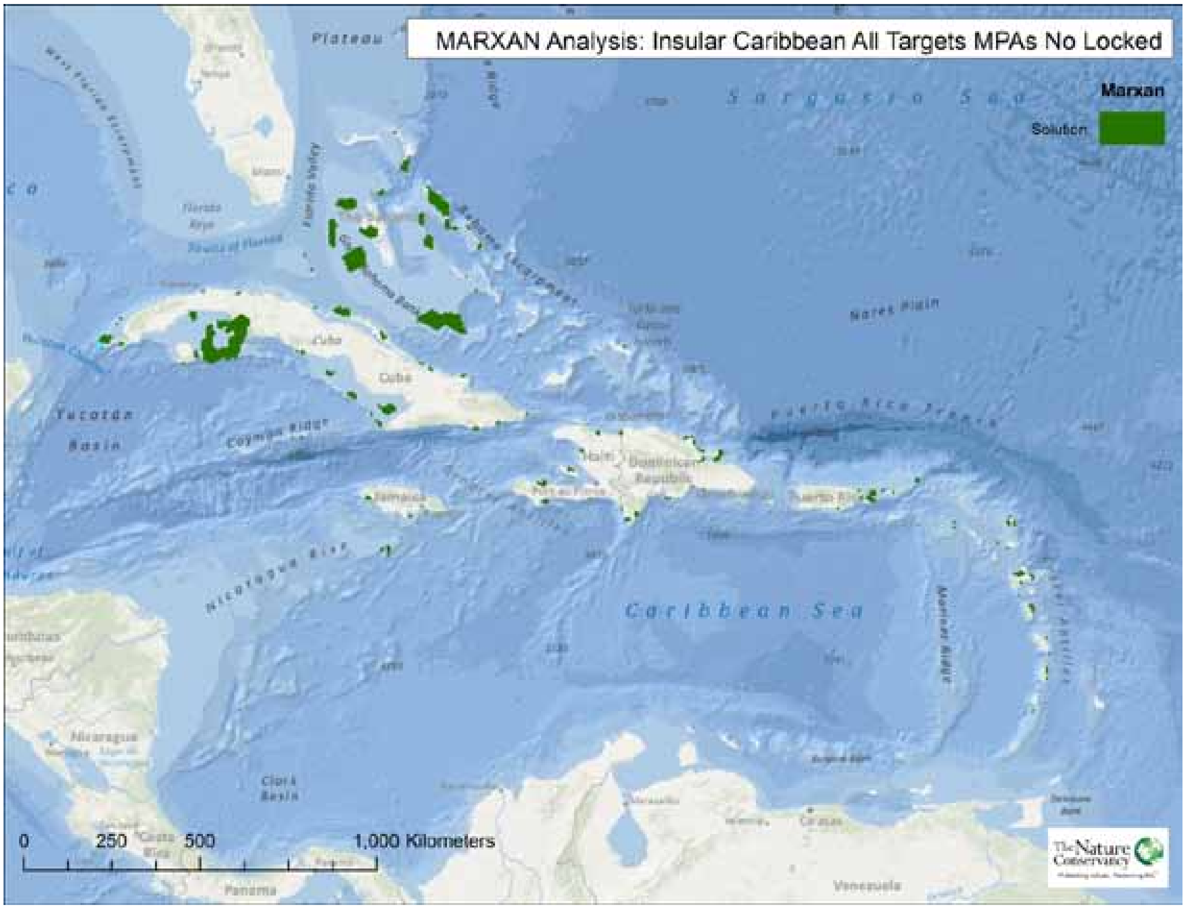
Conservation Feature	Feature Name	Target	Amount Held	Occurrences Held	Target Met
68	Western Caribbean	35379.852	35358.75	61	yes
67	Southwestern Caribbean	48944.248	49415.01	18	yes
69	Southern Gulf of Mexico	9041.096	9058.08	9	yes
66	Southern Caribbean	10927.96	10898.12	11	no
43	Northern Gulf of Mexico	4355.718	4455.72	1	yes
65	Greater Antilles	92425.826	92447.54	182	yes
70	Floridian	18201.036	18938.03	4	yes
64	Eastern Caribbean	18402.834	16418.74	12	no
62	Bermuda	14795.76	73978.8	40	yes
63	Bahamian	58213.472	57939.38	176	yes



Conservation Feature	Feature Name	Target	Amount Held	Occurrences Held	Target Met
68	Western Caribbean	35379.852	35411.38	38	yes
67	Southwestern Caribbean	48944.248	49493.97	17	yes
69	Southern Gulf of Mexico	9041.096	9839.63	3	yes
66	Southern Caribbean	10927.96	10861.51	13	yes
43	Northern Gulf of Mexico	4355.718	4259.45	3	no
65	Greater Antilles	92425.826	92223.76	109	yes
70	Floridian	18201.036	18438.67	5	yes
64	Eastern Caribbean	18402.834	18392.03	14	yes
62	Bermuda	14795.76	13395.16	4	no
63	Bahamian	58213.472	58610.27	46	yes



Conservation Feature	Feature Name	Target	Amount Held	Occurrences Held	Target Met
68	Western Caribbean	35379.852	176899.26	386	yes
67	Southwestern Caribbean	48944.248	53503.49	157	yes
69	Southern Gulf of Mexico	9041.096	9460.66	31	yes
66	Southern Caribbean	10927.96	47295.71	166	yes
43	Northern Gulf of Mexico	4355.718	2435.72	1	no
65	Greater Antilles	92425.826	92402.62	236	yes
70	Floridian	18201.036	15938.03	4	no
64	Eastern Caribbean	18402.834	18403.11	76	yes
62	Bermuda	14795.76	14822.93	3	yes
63	Bahamian	58213.472	58176.06	187	yes



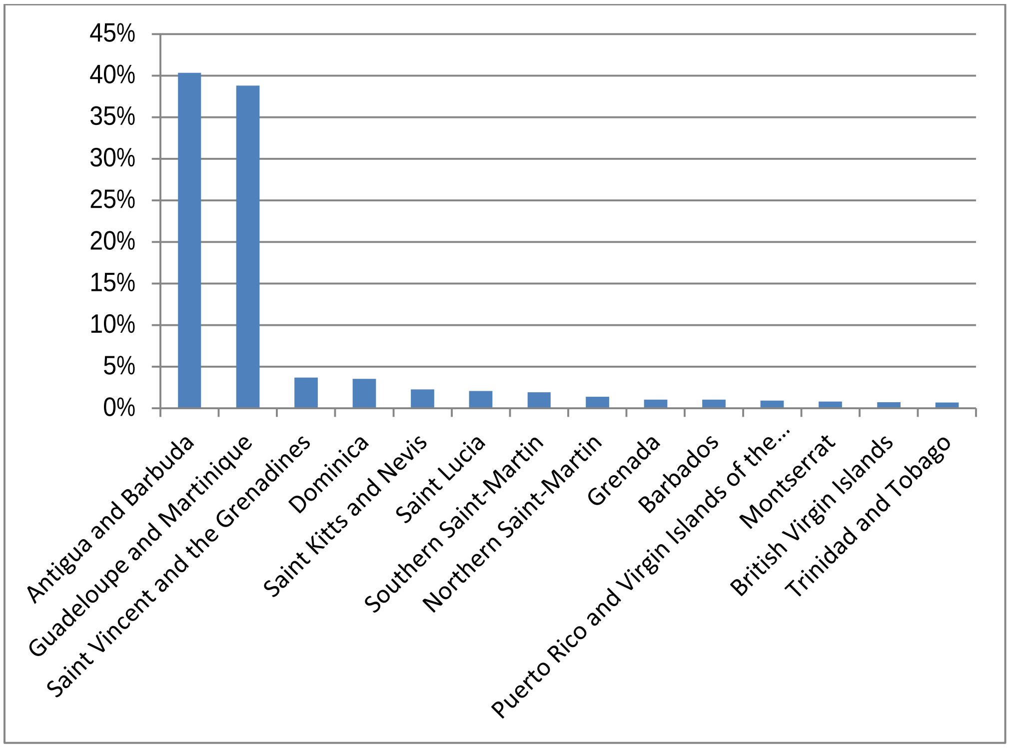
Conservation Feature	Feature Name	Target	Amount Held	Occurrences Held	Target Met
3016	Greater Antilles Rocky Shore	457	493.54	86	yes
2016	Eastern Caribbean Rocky Shore	137.216	137.82	26	yes
1016	Bahamian Rocky Shore	31.932	32.27	13	yes
3019	Greater Antilles Seagrass	599520.26	745500.61	359	yes
2019	Eastern Caribbean Seagrass	55378.566	56087.4	47	yes
1019	Bahamian Seagrass	1098260.308	1098453.17	400	yes
3017	Greater Antilles Sandy Beach	1825.522	2245.58	200	yes
2017	Eastern Caribbean Sandy Beach	359.362	363.18	50	yes
1017	Bahamian Sandy Beach	1845.978	1846.29	102	yes
3010	Greater Antilles Coastal Lagoon	7875.506	16037.92	127	yes
2010	Eastern Caribbean Coastal Lagoon	1034.502	1943.97	27	yes
1010	Bahamian Coastal Lagoon	3408.844	3766.79	73	yes
3012	Greater Antilles Coral Reef	92425.824	103609.84	318	yes
2012	Eastern Caribbean Coral Reef	18402.834	19115.8	46	yes
1012	Bahamian Coral Reef	58213.472	58247.34	299	yes
3013	Greater Antilles Estuary	17662.812	18791.9	66	yes
2013	Eastern Caribbean Estuary	73.598	213.88	14	yes
1013	Bahamian Estuary	596.772	1894.16	21	yes

3014	Greater Antilles Manatee	27.82	28.22	21	yes
1014	Bahamian Manatee	1.64	2.74	2	yes
3015	Greater Antilles Mangrove	187783.34	479177.99	521	yes
2015	Eastern Caribbean Mangrove	1376.398	2572.23	36	yes
1015	Bahamian Mangrove	30789.276	77241.72	192	yes
3018	Greater Antilles Seabird Nesting Area	1.374	1.67	41	yes
2018	Eastern Caribbean Seabird Nesting Area	1.366	1.37	29	yes
1018	Bahamian Seabird Nesting Area	2.172	4.18	68	yes
3021	Greater Antilles SPAGS Medium	70.158	79.92	42	yes
3020	Greater Antilles SPAGS Low	101.268	106.77	56	yes
3022	Greater Antilles SPAGS High	49.268	50.15	26	yes
2021	Eastern Caribbean SPAGS Medium	10.888	11.28	6	yes
2022	Eastern Caribbean SPAGS High	27.052	27.62	16	yes
1021	Bahamian SPAGS Medium	65.418	65.48	31	yes
1020	Bahamian SPAGS Low	32.508	32.93	19	yes
1022	Bahamian SPAGS High	8.636	11.12	5	yes

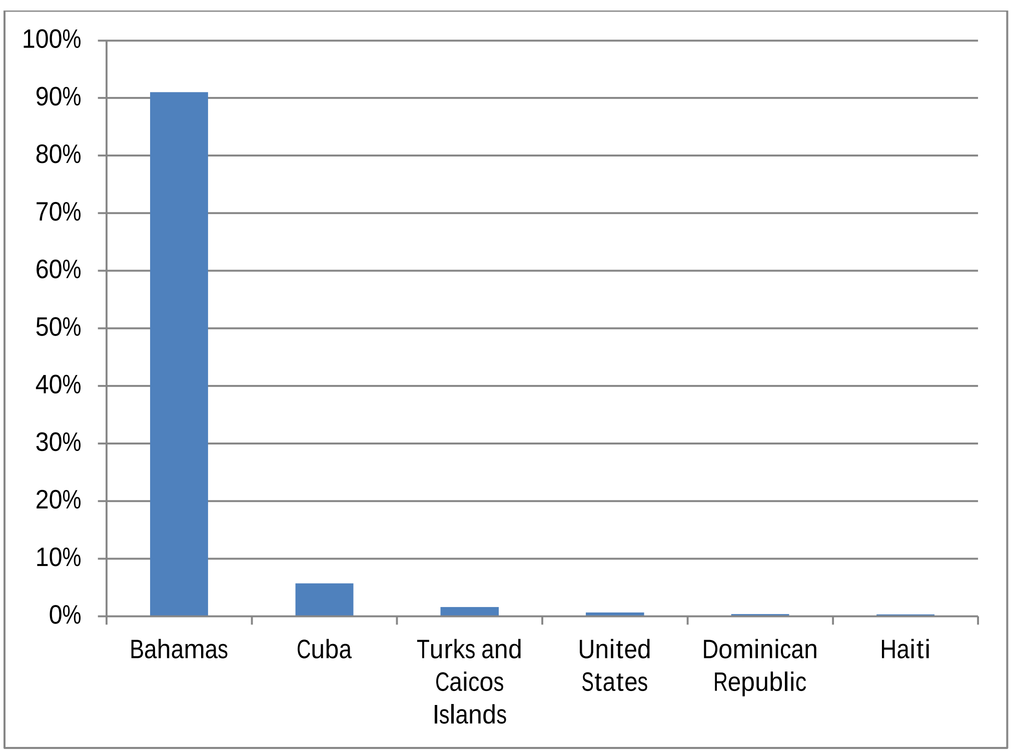
Conservation Feature	Feature Name	Target	Amount Held	Occurrences Held	Target Met
3016	Greater Antilles Rocky Shore	457	454.75	63	yes
2016	Eastern Caribbean Rocky Shore	137.216	137.82	15	yes
1016	Bahamian Rocky Shore	31.932	32.27	7	yes
3019	Greater Antilles Seagrass	599520.26	599802	181	yes
2019	Eastern Caribbean Seagrass	55378.566	55239.97	32	yes
1019	Bahamian Seagrass	1098260.308	1098339.48	372	yes
3017	Greater Antilles Sandy Beach	1825.522	1815.9	89	yes
2017	Eastern Caribbean Sandy Beach	359.362	359.72	28	yes
1017	Bahamian Sandy Beach	1845.978	1850.06	85	yes
3010	Greater Antilles Coastal Lagoon	7875.506	7996.33	61	yes
2010	Eastern Caribbean Coastal Lagoon	1034.502	1598.41	17	yes
1010	Bahamian Coastal Lagoon	3408.844	3281.37	56	no
3012	Greater Antilles Coral Reef	92425.824	92591.56	160	yes
2012	Eastern Caribbean Coral Reef	18402.834	18550.69	37	yes
1012	Bahamian Coral Reef	58213.472	58040.41	262	yes
3013	Greater Antilles Estuary	17662.812	17028.92	22	no
2013	Eastern Caribbean Estuary	73.598	188.12	6	yes
1013	Bahamian Estuary	596.772	611.46	8	yes

3014	Greater Antilles Manatee	27.82	28.53	9	yes
1014	Bahamian Manatee	1.64	1.68	1	yes
3015	Greater Antilles Mangrove	187783.34	191483.9	159	yes
2015	Eastern Caribbean Mangrove	1376.398	1994.83	19	yes
1015	Bahamian Mangrove	30789.276	31548.01	90	yes
3018	Greater Antilles Seabird Nesting Area	1.374	1.38	23	yes
2018	Eastern Caribbean Seabird Nesting Area	1.366	1.4	17	yes
1018	Bahamian Seabird Nesting Area	2.172	2.19	33	yes
3021	Greater Antilles SPAGS Medium	70.158	70.43	26	yes
3020	Greater Antilles SPAGS Low	101.268	101.8	44	yes
3022	Greater Antilles SPAGS High	49.268	49.72	23	yes
2021	Eastern Caribbean SPAGS Medium	10.888	11.36	4	yes
2022	Eastern Caribbean SPAGS High	27.052	26.89	12	yes
1021	Bahamian SPAGS Medium	65.418	65.4	29	yes
1020	Bahamian SPAGS Low	32.508	35.72	16	yes
1022	Bahamian SPAGS High	8.636	11.11	6	yes

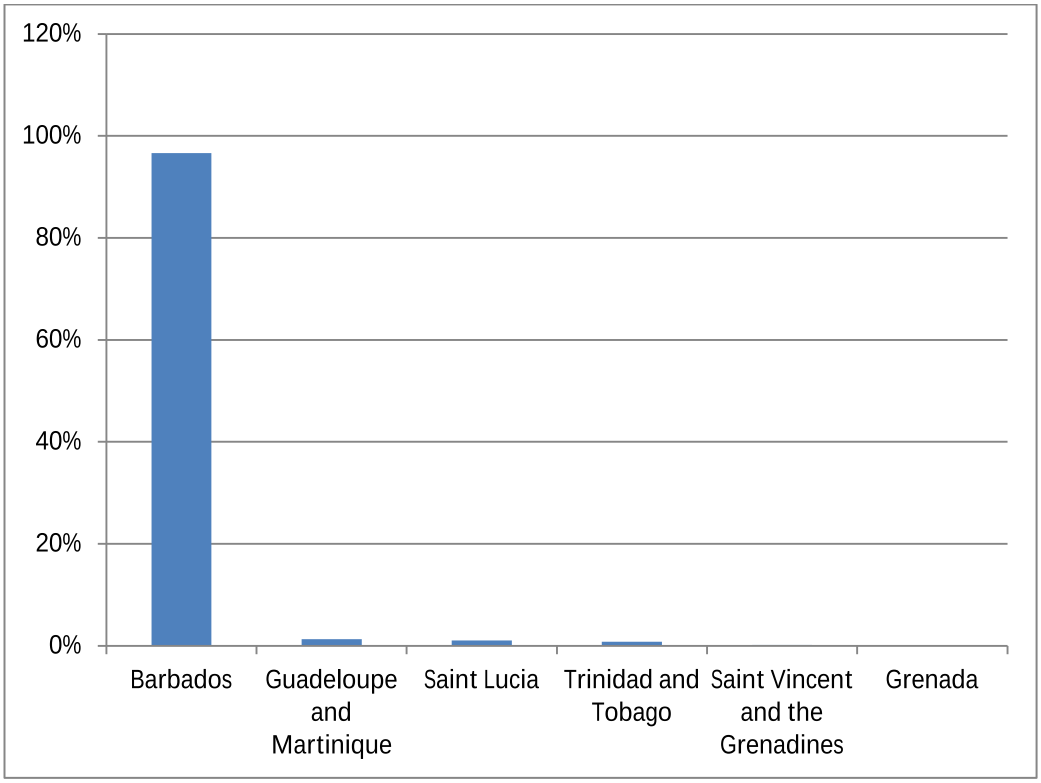
MARINE CONNECTIVITY GRAPHS



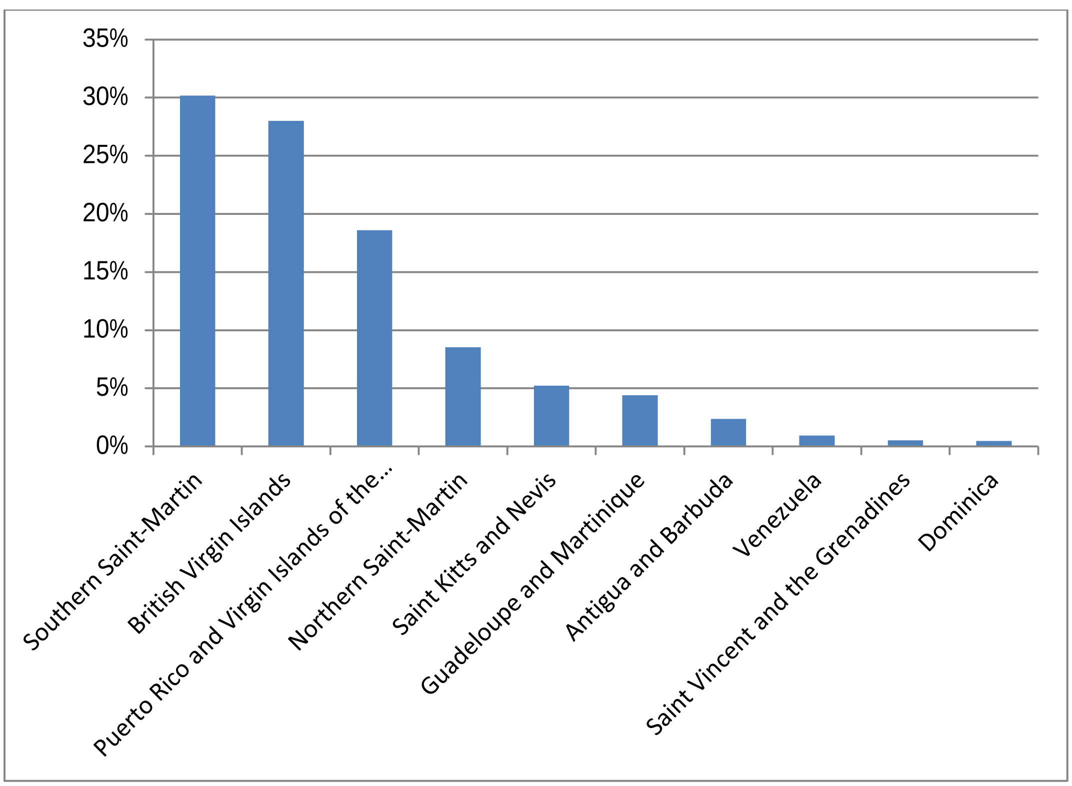
Antigua & Barbuda: Larvae retention by country



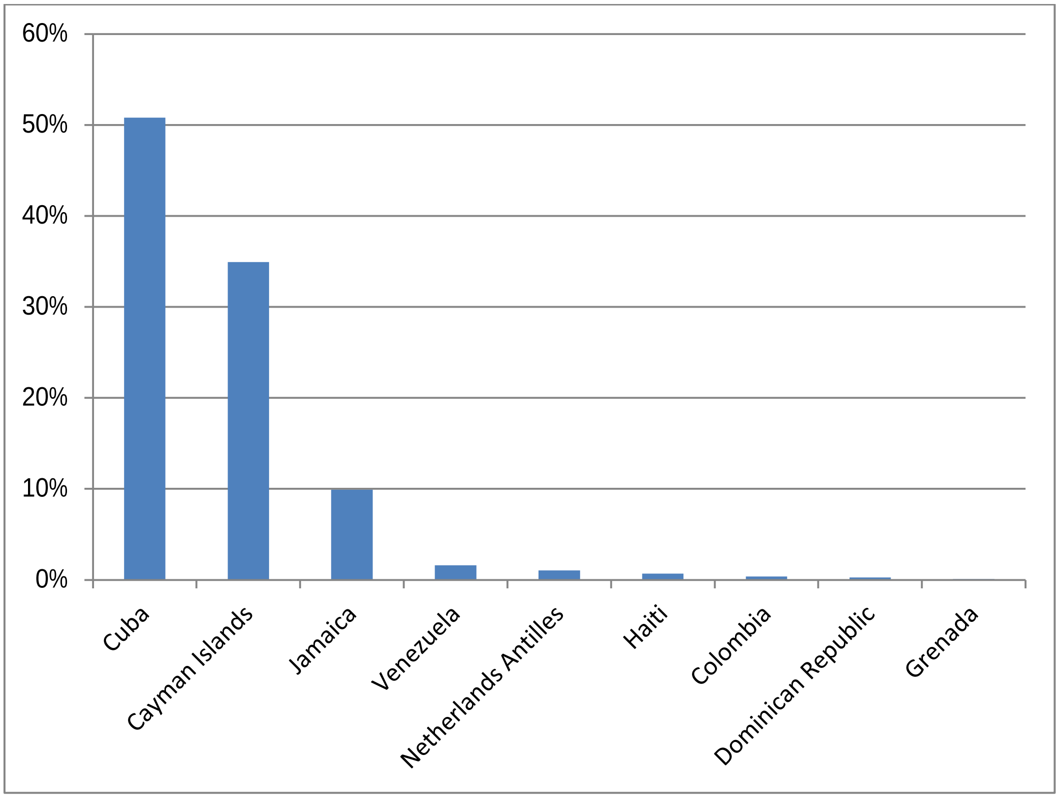
Bahamas: Larvae retention by country



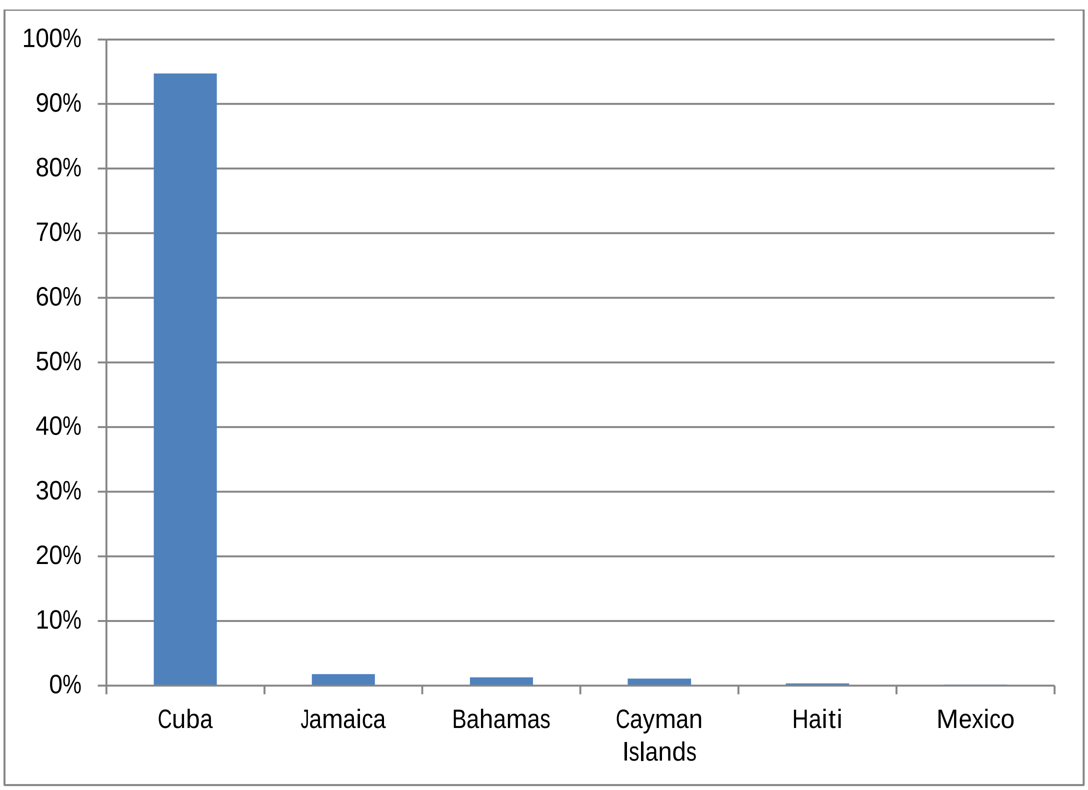
Barbados: Larvae retention by country



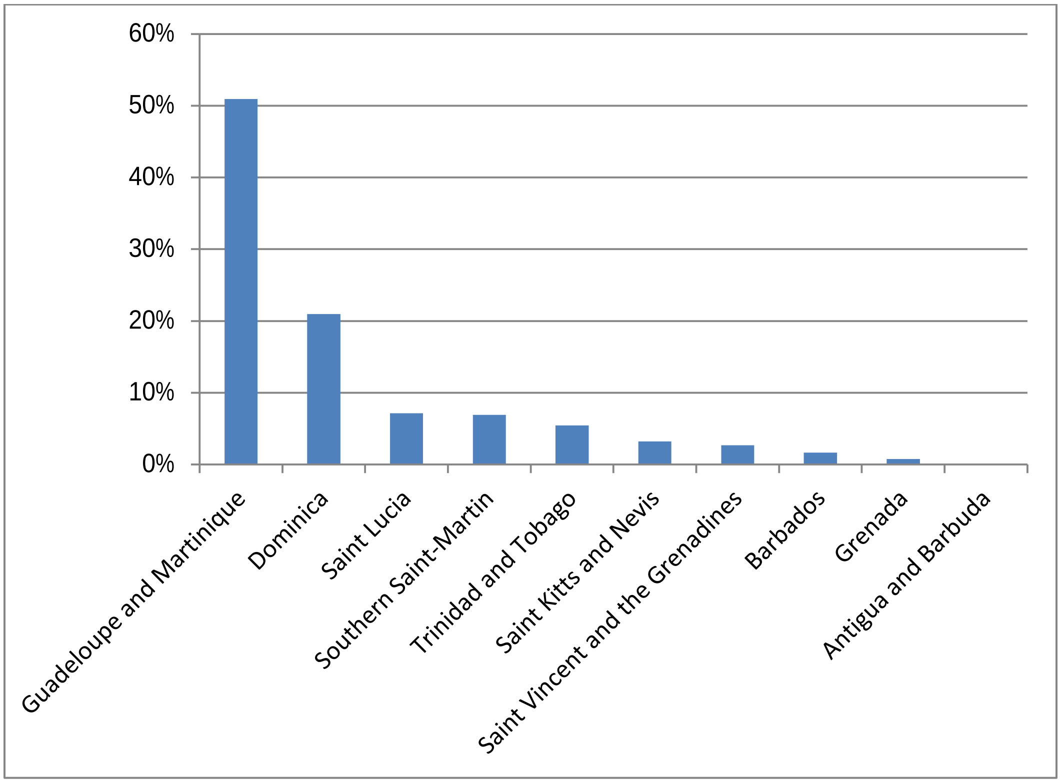
BVI: Larvae retention by country



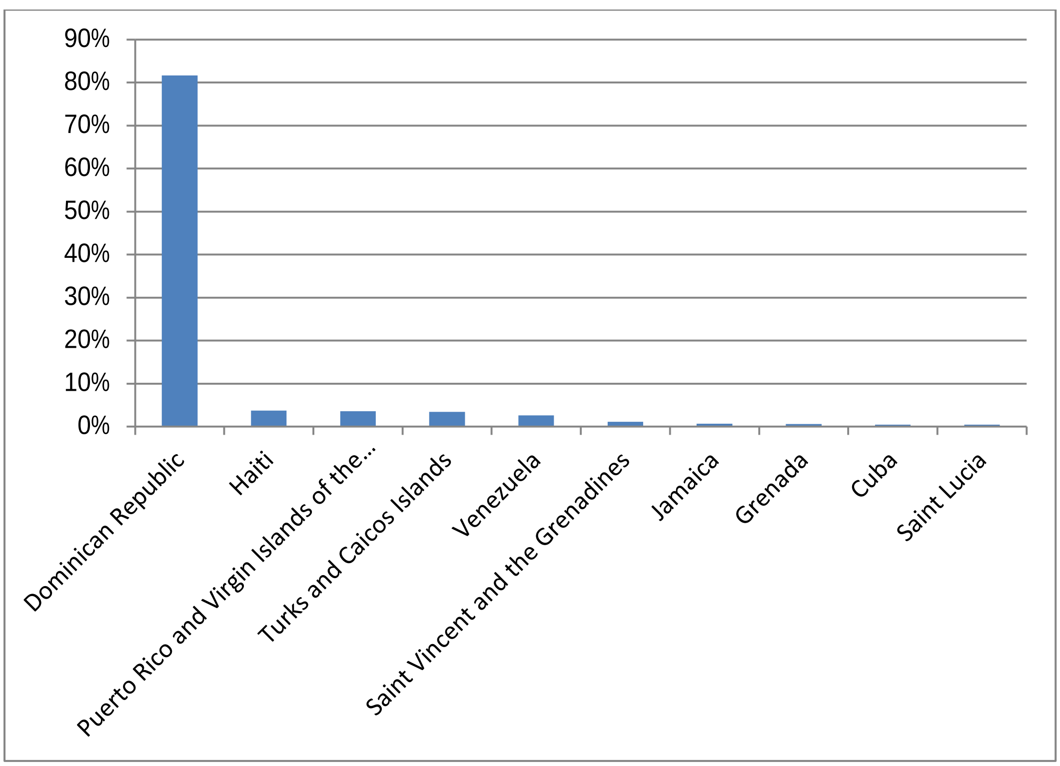
Cayman Islands: Larvae retention by country



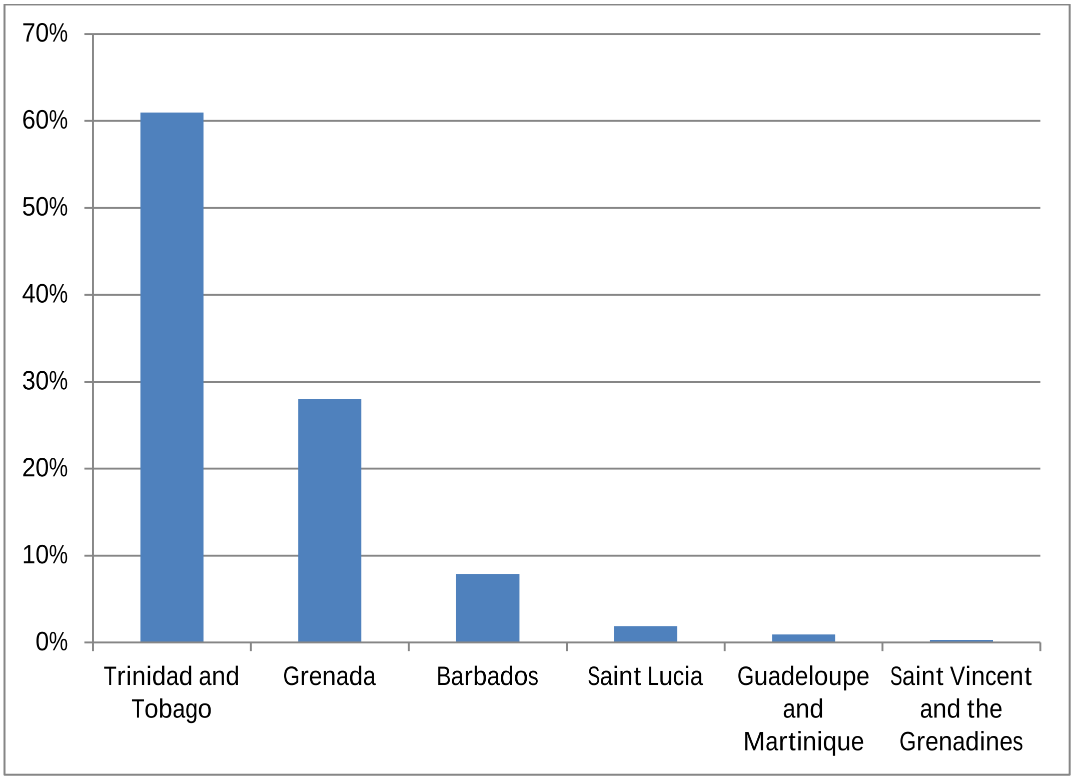
Cuba: Larvae retention by country



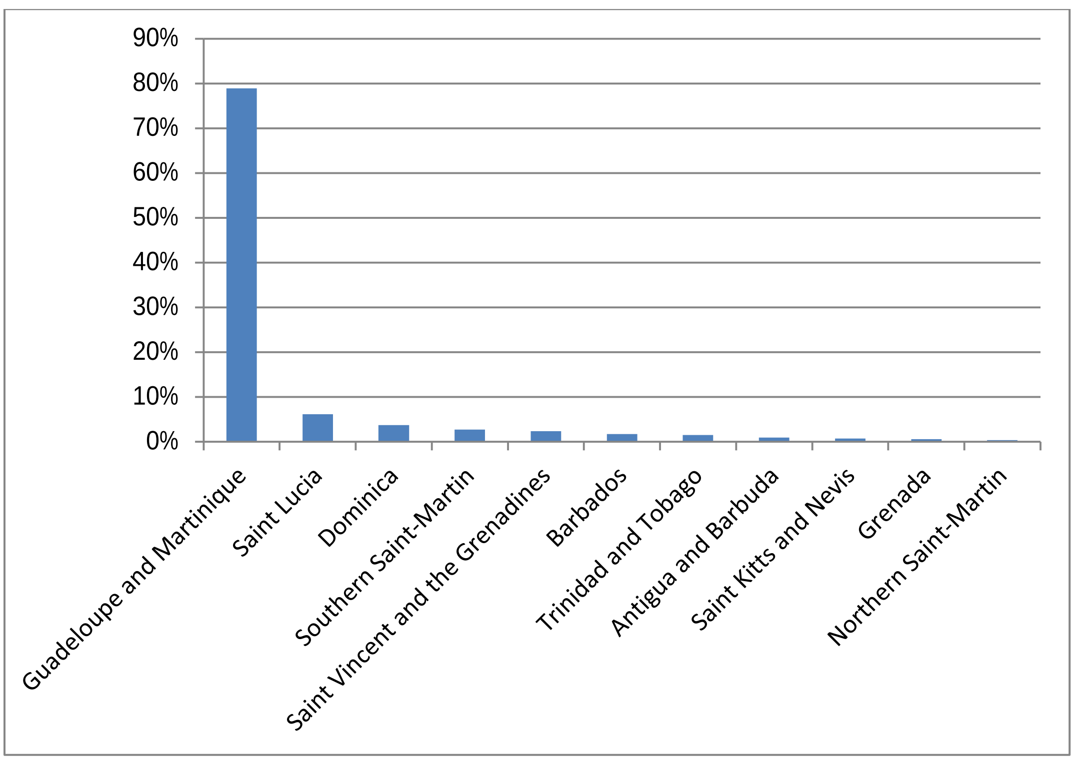
Dominica: Larvae retention by country



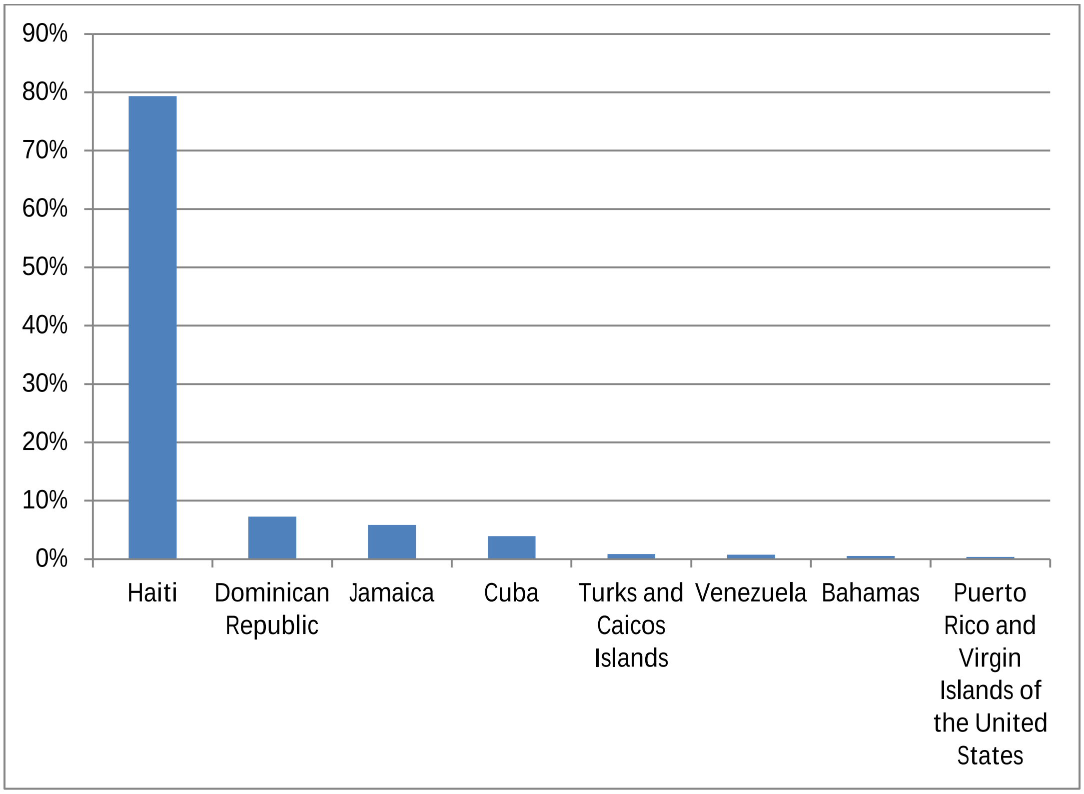
Dominican Republic: Larvae retention by country



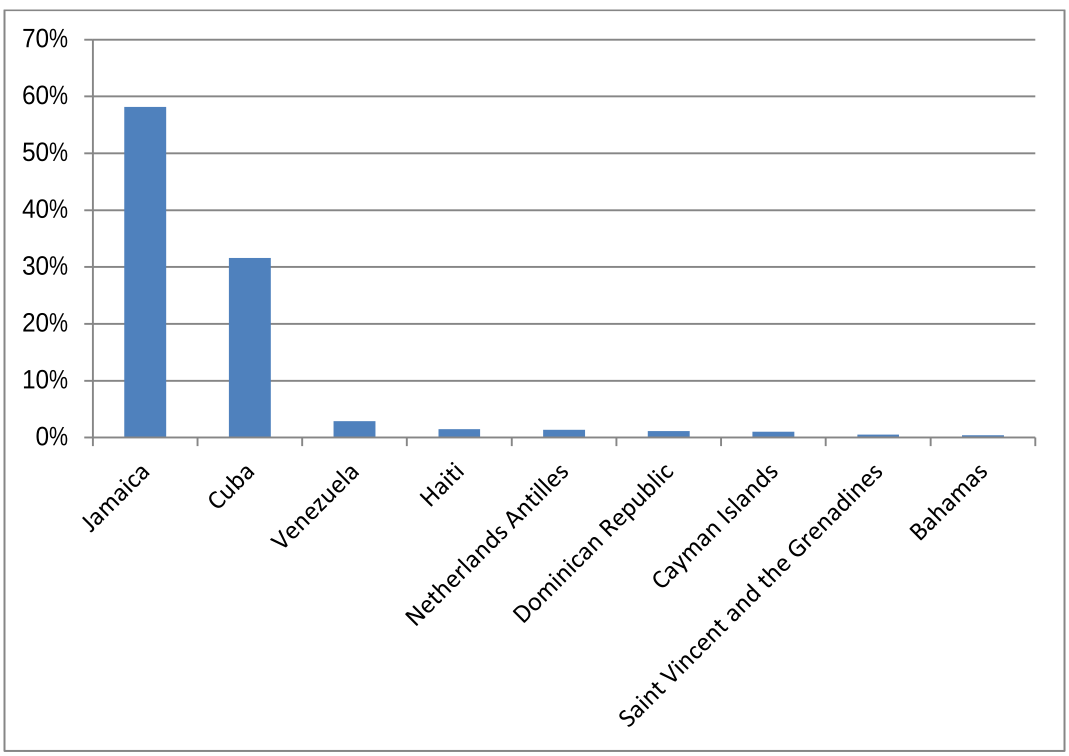
Grenada: Larvae retention by country



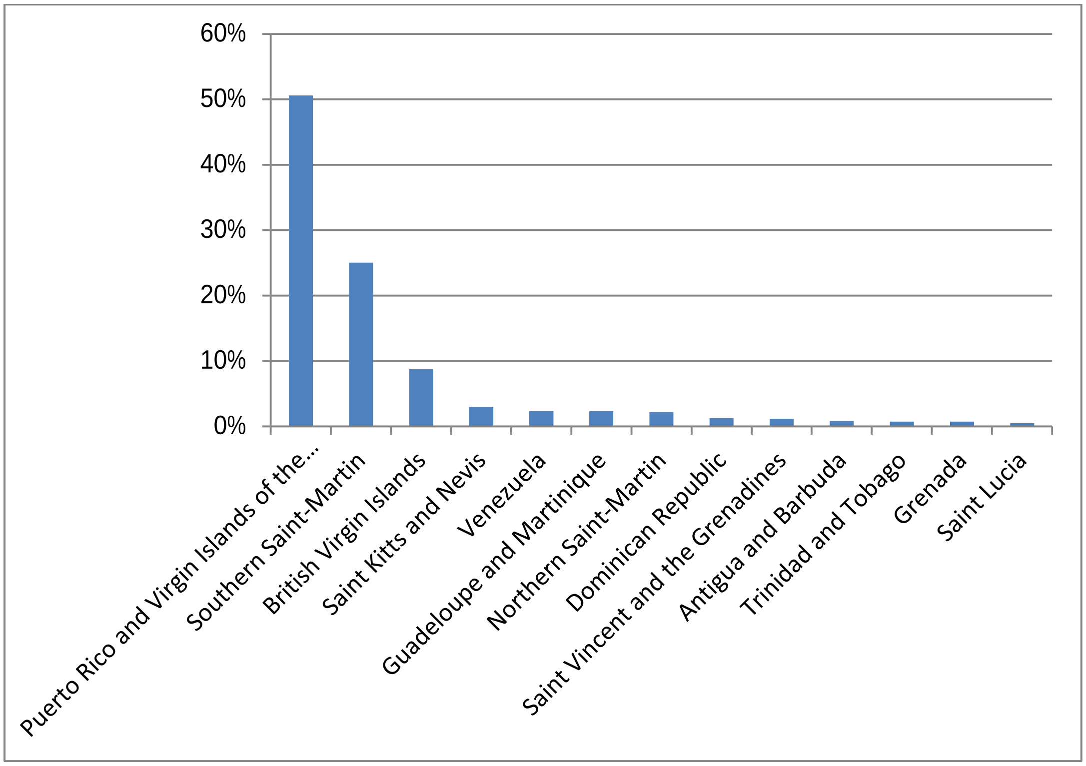
Guadeloupe and Martinique: Larvae retention by country



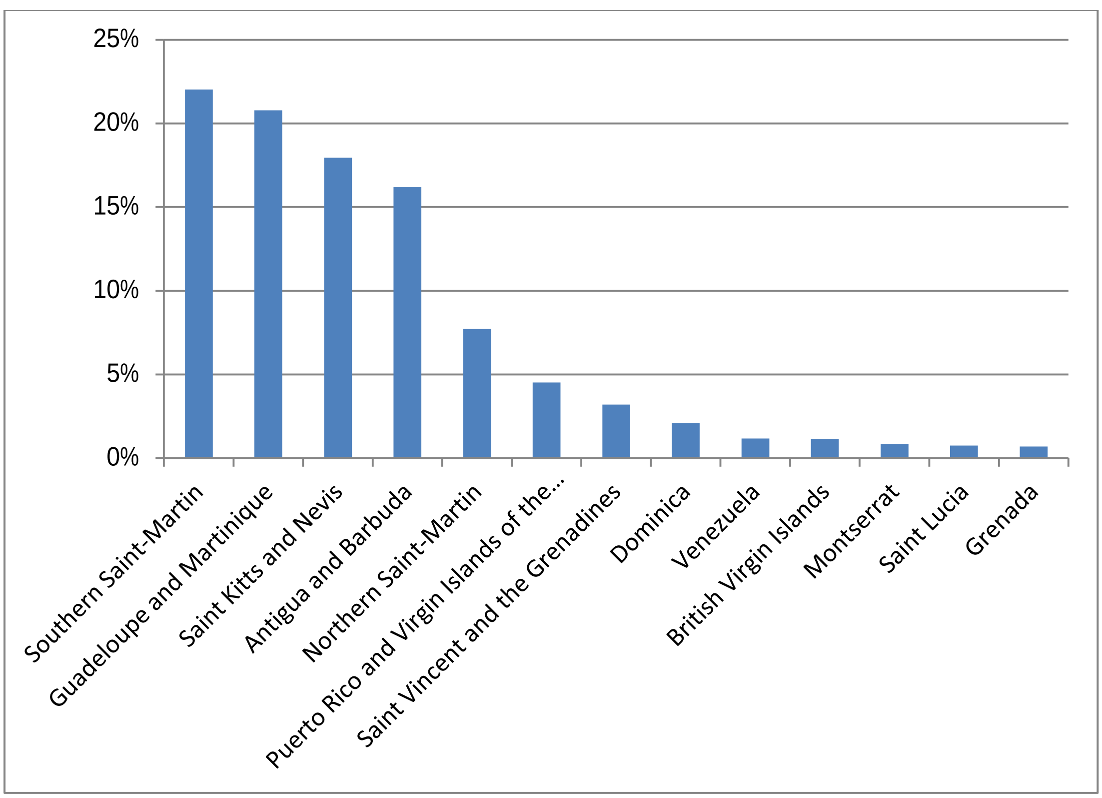
Haiti: Larvae retention by country



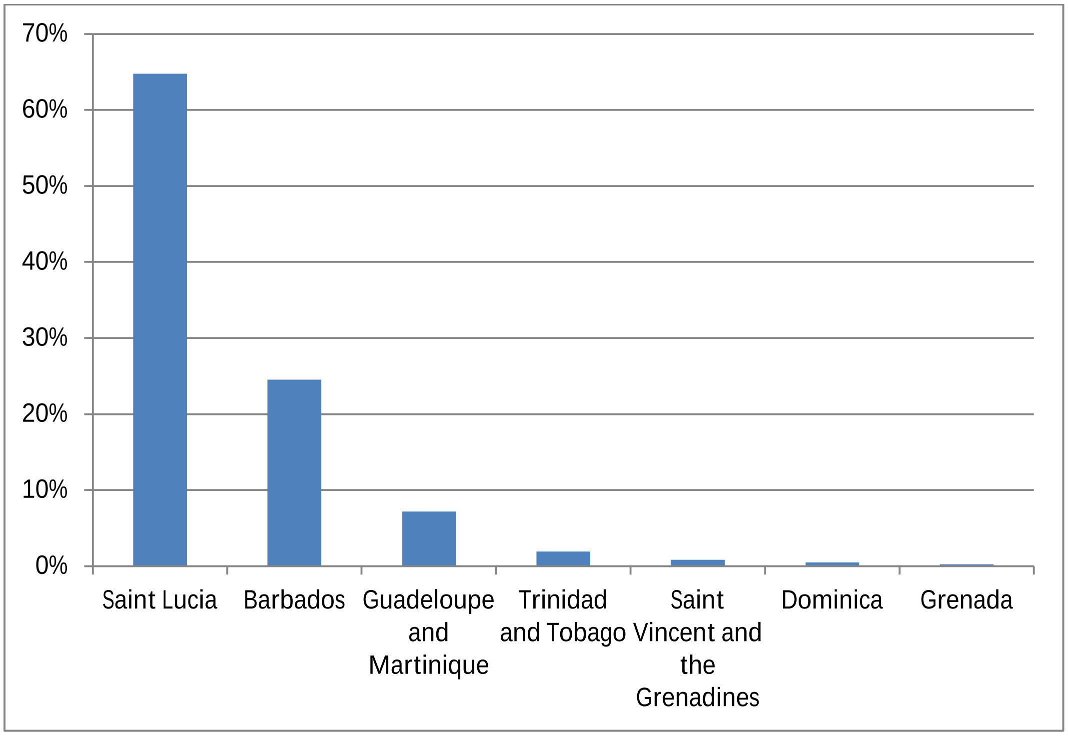
Jamaica: Larvae retention by country



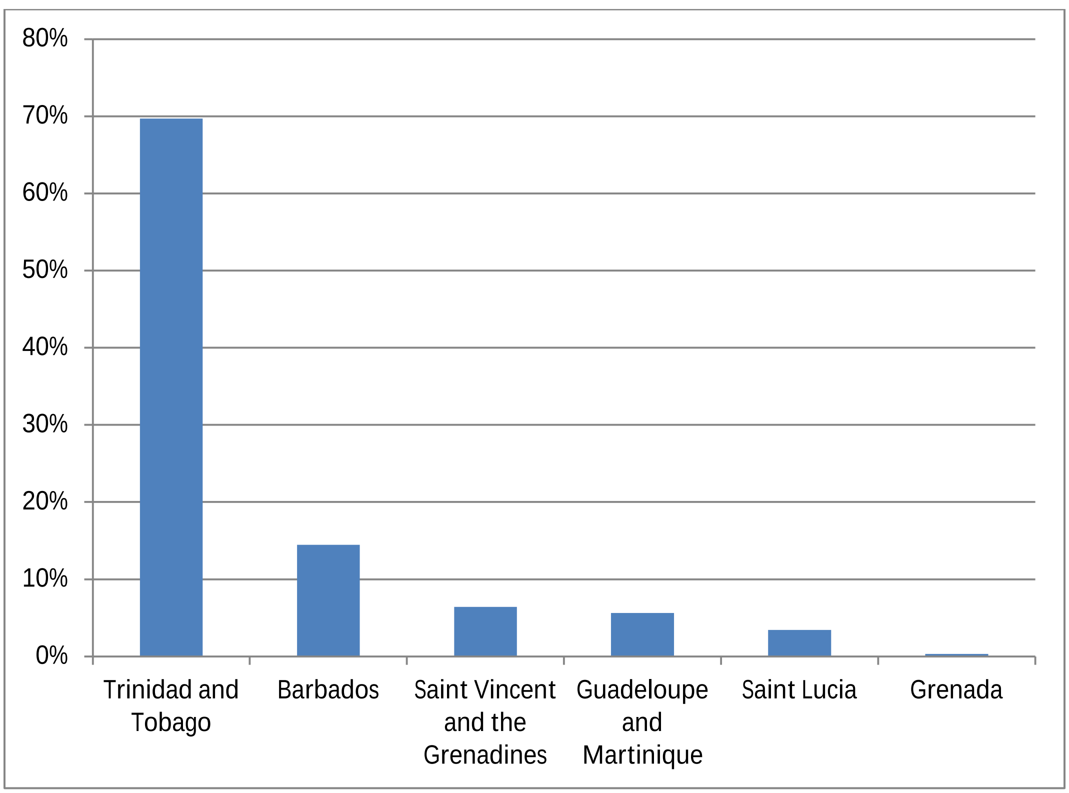
Puerto Rico and the US Virgin Islands: Larvae retention by country



St. Kitts and Nevis: Larvae retention by country



St. Lucia: Larvae retention by country



St. Vincent and the Grenadines: Larvae retention by country