EPA 822-R-21-007

The Biological Condition Gradient (BCG) for Puerto Rico and U.S. Virgin Islands Coral Reefs

TECHNICAL REPORT

September 15, 2021

The Biological Condition Gradient (BCG) for Puerto Rico and U.S. Virgin Islands Coral Reefs

Contributing Authors

Pat Bradley
Tetra Tech; Key West, FL

Ben Jessup
Tetra Tech; Montpelier, VT

Deborah Santavy
US EPA, Office of Research and Development, Gulf Ecosystem Measurement and Modeling Division; Gulf Breeze, FL

Ernesto Weil
Department of Marine Sciences, University of Puerto Rico; Mayagüez, PR

Christina Horstmann
US EPA, Oak Ridge Institute for Science Education Fellow, Office of Research and Development, Gulf Ecosystem Measurement and Modeling Division; Gulf Breeze, FL

Leah Oliver
US EPA, Office of Research and Development, Gulf Ecosystem Measurement and Modeling Division; Gulf Breeze, FL

Contact Information

For more information, questions or comments about this document, please contact Susan Jackson, U.S. Environmental Protection Agency, Office of Water/Office of Science and Technology, 1200 Pennsylvania Avenue, 4304T, Washington DC, 20460 or by email at jackson.susank@epa.gov

Citation

USEPA (U.S. Environmental Protection Agency). 2021. The Biological Condition Gradient (BCG) for Puerto Rico and U.S. Virgin Islands Coral Reefs. EPA 822-R-2-1007. U.S. Environmental Protection Agency, Office of Water/Office of Science and Technology, Washington, D.C

Acknowledgments

We are grateful for the hard work, insights, commitment, and enthusiasm provided by the experts, as listed in the table below. The work of sample review and model development was fraught with a series of disruptive events that hampered communication and scheduling of critical meetings, webinars, and discussions. This included evacuation from Magueyes Island due to Hurricane Isaac in 2012, abruptly terminating the first workshop; the catastrophic impacts of Hurricane Irma to Florida and the USVI, and Hurricane Maria to Puerto Rico in 2017; three government shut-downs that caused all work on the BCG to cease (2013, 2018, 2019); the devastating earthquake swarm in 2019-2020 that struck the southwestern part of Puerto Rico; and the ongoing COVID-19 pandemic. The commitment and dedication of the experts has been humbling and deeply appreciated.

BCG Coral Reef Experts

Affiliation	Expert	Assemblage Expertise
University of Puerto Rico	Richard Appeldoorn	Fish
	Ernesto Weil	Benthic
	Paul Yoshioka	Benthic
	Alberto Sabat	Fish
University of Miami	Jerry Ault	Fish
	Steve Smith	Fish
Smithsonian Institution	Melanie McField	Benthic/Fish
	David Ballantine	Benthic
San Juan Bay Estuary Program	Jorge Bauzá	Benthic
NOAA	Lisamarie Carrubba	Fish
	Graciela Garcia Moliner	Fish
	Randy Clark	Benthic
	Brandi Todd	Benthic
Nova Southeastern University	Brian K. Walker	Benthic/Fish
Puerto Rico Department of Natural and Environmental Resources	Craig Lilyestrom	Fish
	Ernesto Diaz	Benthic
	Miguel Canals	Benthic
HJR Reefscaping	Michelle Schärer	Fish
	Héctor Ruiz	Benthic
University of the Virgin Islands	Tyler Smith	Benthic/Fish
University of North Carolina, Wilmington	Alina Szmant	Benthic
US Geological Survey	Caroline Rogers	Benthic
National Park Service	Jeff Miller	Benthic
Marine Biological Laboratory	Loretta Roberson	Benthic
The Nature Conservancy	Aaron Hutchins	Benthic

CSS-Inc., Fairfax, VA; Under Contract to NOAA	Chris Jeffrey	Benthic
	Simon Pittman	Fish
Vicente & Associates	Vance Vicente	Benthic
Protectores de Cuencas	Roberto Viquiera	Benthic
US EPA	David Cuevas	Benthic
	Evelyn Huertas	Fish
	William Fisher	Benthic
	Debbie Santavy	Benthic (facilitator)
	Christina Horstmann (ORISE)	Benthic (facilitator)

In addition to expert deliberations and decisions, Ernest Weil and Caroline Rogers provided expertise and analysis on specific topics that informed the model calibration and are included in appendices L and T respectively.

We thank the Caribbean Coral Reef Institute for hosting the 1st and 4th workshops on Magueyes Island; the El Yunque National Forest Headquarters for providing the conference facilities for the 2nd workshop; and the Caribbean Landscape Cooperative (CLCC) and the International Institute of Tropical Forestry (IITF) for providing the conference facilities for the 3rd workshop. The BCG workshops were convened through the collaborative efforts of the U.S. Environmental Protection Agency (EPA) Office of Research and Development (ORD), Office of Water (OW), and Region 2.

Debbie Santavy and Christina Horstmann provided extensive technical support and expertise fromproject start to finish. Leah Oliver, EPA ORD, provided expertise to define the generalized stressor gradient. Their contribution exemplifies the type of partnership with the EPA OW and the Regions that benefits state, tribal and territorial water programs. Thorough final technical editing and reference reviews were provided by Debbie Santavy, Alex Almario (EPA ORD), and Christina Horstmann with unfaltering technical support, guidance, and encouragement from Sandy Raimondo (EPA ORD).

Notice and Disclaimer

Cover Photo:

BCG Experts, Caribbean Coral Reef Institute, Magueyes Island, La Parguera, Puerto Rico March 12-14, 2019. Photo credit: Susan Jackson (U.S. EPA).

Table of Contents

Appendices

Acronyms

BCG – Biological Condition Gradient
CWA – Clean Water Act
DEMO – Demographic benthic sampling method
DPNR – Department of Planning and Natural Resources (USVI)
EPA – US Environmental Protection Agency
FKNMS – Florida Keys National Marine Sanctuary
GIS – Geographic Information System
GSA – Generalized Stressor Axis
LDI – Landscape Development Intensity Index
LPI – Linear Point Intercept benthic sampling method
MPA – Marine Protected Area
NCRMP – National Coral Reef Monitoring Program (NOAA)
NMFS – National Marine Fisheries Service (NOAA)
NOAA – National Oceanic and Atmospheric Administration
NPS – National Park Service
ORD – Office of Research and Development (EPA)
PR – Puerto Rico
QA/QC – Quality Assurance/Quality Control
SST – Sea Surface Temperature
ST – Sediment Threat
USCRTF – United States Coral Reef Task Force
USN – United States Navy
USVI – United States Virgin Islands
UVI – University of the Virgin Islands
WQS – Water Quality Standards
WRI – World Resources Institute

Glossary: See Appendix A

List of Tables

List of Figures

Executive Summary

The Biological Condition Gradient (BCG), initially developed by freshwater scientists, has been applied to the Caribbean coral reef ecosystem. The conceptual BCG describes how biological attributes of aquatic ecosystems change along a gradient of increasing human disturbance. The conceptual model has been calibrated for application to the near shore coral reefs of the U.S. Virgin Islands (USVI) and Puerto Rico. The model can be used to support biological assessments of reef condition, monitor for changes in condition, identify high quality reefs, evaluate effectiveness of Best Management Practice (BMP), and support biological criteria development.

Coral reef ecologists and fisheries scientists with specific knowledge of the Caribbean region evaluated site-specific quantitative data from diver-based visual surveys on species abundance, community assemblage structure, and benthic habitat composition to develop quantitative decision rules. The experts then:

- developed a conceptual model
- assigned BCG attributes to individual species
- assigned BCG Levels to survey sites based on the sample composition, including taxa characteristics such as trophic group, organism condition, and BCG attribute assignments
- developed preliminary narrative decision rules for semi-quantitative BCG models
- and developed, reconciled, revised, and tested quantitative decision rules for benthic organisms and fish

The experts agreed that BCG Level 1 sites (as naturally occur) no longer exist in the Caribbean region. Historic data were used to help define BCG Level 1 conditions in absence of empirical data. BCG Level 1 is defined narratively and provides context for interpreting Levels 2 through 6.

In calibrating the BCG models, the experts used coral reef condition data from both EPA 2010 and 2011 surveys in Puerto Rico, and NOAA's National Coral Reef Monitoring Program (NCRMP) 2013 – 2015 surveys in Puerto Rico and the USVI.

The models were calibrated separately for benthic and fish assemblages. Each model includes a cascade of rules for membership at each BCG Level, starting with conceptual rules for Level 2 and proceeding with testable rules for Levels 3 through 5. Samples that failed at all Levels automatically were evaluated as Level 6.

Rules were calibrated through a process that prompted experts to first conceptualize good, fair, and poor reef conditions and to describe reefs in these broad condition categories. Experts characterized fish and coral species attributes based on native range, endemism, and sensitivity to pollution. Narrative decision rules were based upon experts' expectations of the fish and benthic assemblages at each BCG Level. Experts reviewed data for taxa attributes and traits (e.g., fish: trophic group) present at each site. With support of the technical analysts, the narrative rules were translated into numeric rules that distinguished between BCG Levels based on measurable sample characteristics (metrics). The numeric rules were compiled for application as a BCG expert decision model that could accurately and transparently replicate the decisions that the experts expressed during sample reviews.

The predictive BCG model was accurate, though not perfect, in replicating assessment decisions made by the experts. Predictions of BCG Levels from model application agreed with expert consensus of BCG Levels for 92% and 82% of the fish sites (calibration) and for 84% and 89% of the benthic sites (calibration). The model predictions for all sites (100%) were within one BCG Level of the expert consensus. The experts also tested potential transferability of the Puerto Rico fish model to a different jurisdiction (i.e., the Florida Keys and Dry Tortugas). A set of 14 fish samples was reviewed by the experts, and the quantitative BCG model developed for Puerto Rico and the USVI was applied. The model was 79% accurate in replicating the experts' assessments for the Florida Keys calibration.

The experts identified areas for further research that could improve the rigor of the models. These included refinement of data collection methods to increase both measurement specificity and sampling efficiency; calibrating the model with surveys from relatively unimpaired areas elsewhere in the Caribbean (and perhaps from years of long-term data such as are available from the National Park Service for St John and St Croix); taxa trait and metric refinement; classification by depth stratification; and development of a generalized stressor axis that would include land-based pollution, fishing pressure and water temperature.

The fish and benthic BCG models can be combined for a robust interpretation since these diverse assemblages can respond differently to stressors. While the BCG model was developed using data from Puerto Rico and the USVI, the BCG general framework could potentially be applied to other coral reef ecosystems. This was demonstrated for sites from the Florida Keys and Dry Tortugas.

Introduction

Since 2012 the US Environmental Protection Agency (EPA) and a group of scientific coral reef experts have collaborated to develop a Biological Condition Gradient (BCG) model for the coral reefs of Puerto Rico and the U.S. Virgin Islands (USVI). This report summarizes the process used to derive a predictive model of the BCG for coral reef fish and benthic assemblages. This report can be used by coral reef managers in Puerto Rico and the USVI to develop and implement elements of a biological monitoring and assessment program.

Beginning in 2000, EPA collaborated with freshwater biologists and managers from across the United States to develop and implement the BCG (Davies and Jackson 2006; EPA 2016). The BCG is a conceptual framework (**Figure 1**) that describes how biological attributes of aquatic ecosystems (i.e., biological condition) are expected to change along a gradient of increasing anthropogenic stress (e.g., physical, chemical, and biological impacts).

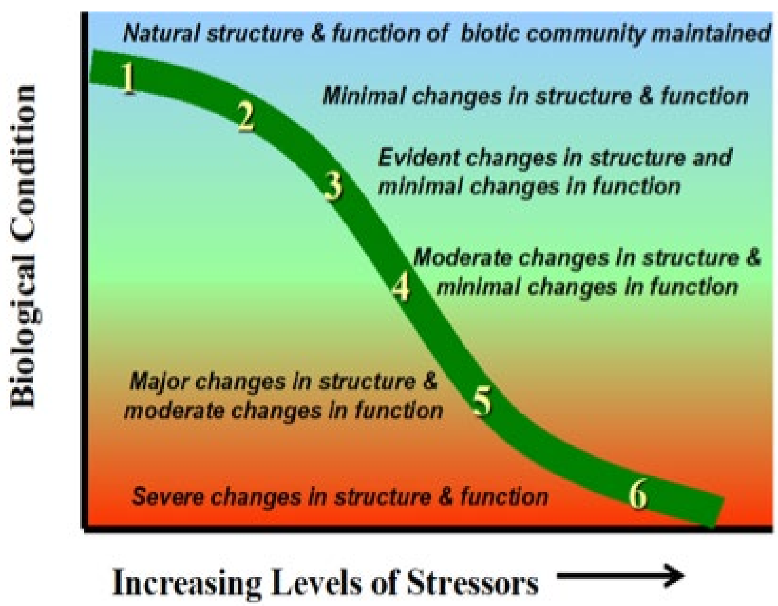


Figure 1. The Biological Condition Gradient (BCG).

Two Important BCG Concepts

Two important concepts are fundamental to the BCG framework: Attributes and Levels (see text box). The attributes are standard descriptions of taxa characteristics that help with interpreting community composition and function (**Figure 2** and **Appendix B**). In the BCG model- building context, attributes are coded using Roman numerals I – VI. Attributes II – V are generally related to taxa endemism and pollution tolerance associated with a generalized stressor gradient. Attribute I describes specialist, historically important, or endemic taxa. Attribute VI describes non-native taxa. Attributes VII – X pertain to organism condition, system performance, and physical-biotic interactions, and these have not typically been used in model development.

BCG Attributes

Attributes include properties of the assemblage (e.g., tolerance, rarity, native-ness) and organisms (e.g., condition, function). In the BCG model-building exercise, BCG attributes I – VI are assigned to taxa (see Figure 2 and Appendix B).

BCG Levels

BCG Levels describe levels, or tiers, of biological response to increasing amounts of stressors. Six BCG Levels are defined ranging from biological conditions found at no or low amounts of stressors (Level 1) to those found at high amounts of stressors (Level 6) (Figure 1 and Appendix C).

BCG Levels are standardized descriptions of biological condition related to assemblage structure, function, and sensitivity to stressors (**Figure 1** and **Appendix C**). BCG Level 1 describes an assemblage that occurs when human disturbance is entirely or almost entirely absent. This is an undisturbed condition as naturally occurs. Level 1 conditions are rarely observable in any aquatic environment, especially given ubiquitous stressors introduced by global phenomena such as climate change and atmospheric deposition. Level 6 conditions assemblages have severely altered structure and function compared to natural expectations. Levels 2 – 5 have successively decreasing resemblance to biological integrity. Levels 2-5 are most often observed during BCG calibration exercises.

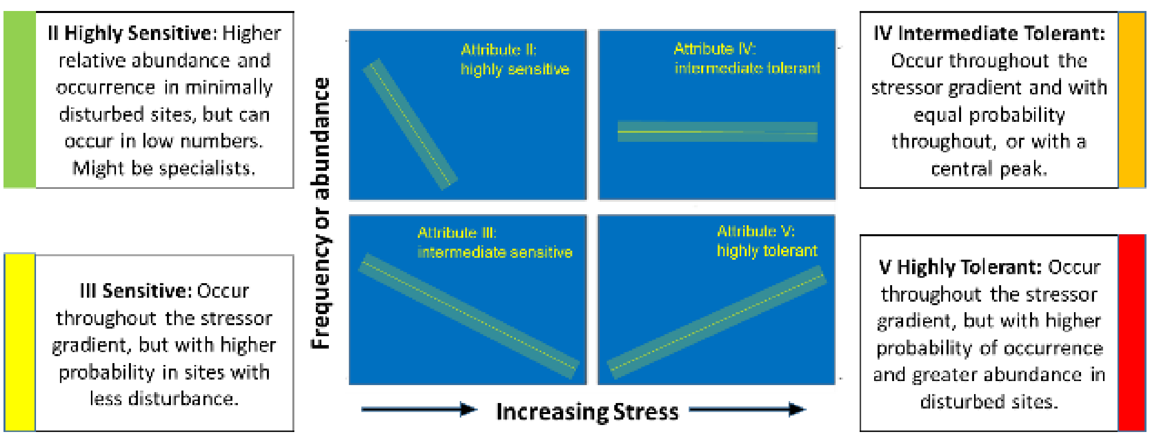


Figure 2. Patterns of frequency or abundance in relation to increasing stress associated with the BCG Attributes assigned to fish and stony coral taxa. Attributes II – V are based on taxa specialization, endemic or native status and stressor tolerance. Attributes I (endemic, specialist species) and VI (non-native species) are not shown in the Figure because they are not necessarily associated with the stressor intensity shown on the x-axis.

The BCG is now a recognized tool in the water quality management toolbox. The BCG builds upon and complements other tools (e.g., biological indices, models, and statistical approaches and guidance) to provide a more refined and detailed measure of biological condition and will help states and territories to:

- More precisely define and measure biological condition for specific waters
- Identify and protect high quality waters
- Evaluate potential for improvement in degraded waters and track improvements
- Develop biological criteria

- Clearly communicate the likely impact of water quality management decisions to the public
- Promote similarity of assessments and endpoints across different geographic area (e.g., states, territories, etc.)

The BCG can support CWA programs such as 305(b) assessments and reports, 303(d) listing of impaired waters, and TMDL program implementation. It can also be used by federal, state, and territorial managers in support of other coral reef and fisheries management programs (**Table 1**).

Table 1. Potential applications of the BCG for Existing Coral Reef Management Programs (modified from Bradley et al. 2010). Continued on next page.

Management Area	**Description**	**Application of the BCG**
Marine Protected Areas (MPAs)	Selecting MPA Sites	• To identify waterbodies that have outstanding biological condition and require protection
	Managing MPAs	• To establish thresholds against which to measure effectiveness of MPAs
	Effectively manage the waters between MPAs	• With establishment of designated uses, to protect those uses (i.e., ecosystem connectivity)
Managing Fisheries	Eliminate open-access fisheries in coral reef ecosystems and establish sustainable fisheries regulations	• To establish levels (e.g., taxa richness, abundance) expected to sustain reef fisheries • Degradation can trigger changes in fishery practices and regulations
	Restricting the species being selected (e.g., coral reef herbivores, including parrotfish)	• To establish expected or desired levels of individual species (e.g., abundance, biomass) • Degradation can trigger changes in fishery practices and regulations
Managing Tourism	Mooring Buoys	• To identify locations with outstanding biological condition that would benefit from the protection of mooring buoys
	Permits – diving, fishing, boating	• With establishment of designated uses, to protect those uses
Watershed Management	Developing and implementing watershed management plans	• To support setting goals for watershed and regional planning • To prioritize watershed goals and actions • To establish thresholds against which to measure effectiveness of permits or other management actions
Coastal Zone Management	Regulating Coastal Development	• To support setting goals for watershed and regional planning • To prioritize watershed goals and actions • To develop management plans
Habitat Connectivity	Maintain connectivity between coral reefs and associated habitats such as mangroves, sea grass beds, and lagoons	• All nearshore environments are protected by the Clean Water Act (CWA) • Coral reefs, mangroves, sea grass beds, and lagoons can be specifically protected when they are identified in water quality standards
Damage Assessment and Restoration	Restoring coral reefs or seagrass meadows damaged by boats and anchors	• To establish thresholds against which to measure effectiveness of restoration efforts.

Managing Endangered Species (Endangered Species Act)	Protecting rare, threatened, and endangered species	• To establish expected or desired levels of individual species (e.g., abundance, biomass). • To establish thresholds against which to measure effectiveness of legal protection.
National Environmental Policy Act (NEPA) of 1969	Environmental Impact Statements	• To identify where site-specific criteria modifications may be needed to effectively protect a waterbody. • To assess the overall ecological effects of regulatory actions.

Problem Statement

More than half of the U.S. population lives in coastal counties - areas that border oceans and coasts, bays, estuaries, and coral reefs (NOAA 2014a). In the states of Florida and Hawai'i and the Commonwealth of Puerto Rico, the USVI, Guam, American Samoa, and the Commonwealth of the Northern Marianas (CNMI), nearly everyone lives within 100 km of the coast. In subtropical and tropical states and territories, coral reefs are ecosystems of concern. Coral reefs provide many important ecosystem services such as: protection of coastlines from ocean storms, support of significant fisheries and biodiversity, resource of sand for beaches and coral rock for construction, tourism and recreation for locals and visitors, and sources of novel pharmaceuticals and medicines. They are integral to many island and coastal traditions, economies, and cultures.

Coral reef ecosystems are declining around the world (Wilkinson 2004, 2008; Bellwood et al. 2004; Pandolfi et al. 2005; Bruno and Selig 2007; Knowlton and Jackson 2008; Hughes et al. 2018). Climate change related impacts (elevated sea surface temperatures causing increased bleaching, disease, and mortality; and more frequent and intensive tropical storms causing physical damage to the reef structure) are affecting coral reefs globally (Hughes et al. 2003; Hoegh-Guldberg et al. 2007, 2011, 2017; Carpenter et al. 2008; Knowlton and Jackson 2008). Local anthropogenic stressors (e.g., polluted runoff from agriculture and unsustainable land-use practices, intense fishing pressure, ship groundings, etc.) also contribute directly to reef decline and can exacerbate climate change impacts (Rogers 1990; Edinger et al. 1998; Jackson et al. 2001; Precht et al. 2001; Fabricius 2005; Mora 2008; Bejarno and Appeldoorn 2013; Vega Thurber et al. 2014; Ennis et al. 2016; Robinson et al. 2017; Moustaka et al. 2018*).* While local managers have little control over climate change, they may be able to substantially reduce local anthropogenic stressors by developing and enforcing laws, regulations and policies for waterbody activities, and watershed land use.

On June 11, 1998, President Clinton signed Executive Order 13089 for Coral Reef Protection that directed all federal agencies to protect coral reef ecosystems to the extent feasible, and instructed agencies to develop coordinated, science-based plans to restore damaged reefs as well as mitigate current and future impacts on reefs, in the United States and globally. Executive

Order 13089 also established the interagency U.S. Coral Reef Task Force (USCRTF) that works to develop and implement comprehensive, multidisciplinary, and coordinated approaches to preserve and protect U.S. coral reef ecosystems and encourage sound coral reef conservation practices globally. The Task Force seeks to use existing U.S. agencies' programs, statutory authorities, competencies, and capabilities to promote coral reef conservation consistent with U.S. law and treaty obligations. The USCRTF includes leaders of 12 Federal agencies, seven U.S. States, Territories, and Commonwealths (Florida, Hawaii, Puerto Rico, the USVI, American Samoa, Guam, and the Northern Marianas) and three Freely Associated States (Federated States of Micronesia, Republic of the Marshall Islands, and the Republic of Palau).

The U.S. Clean Water Act (CWA) (33 USC § 1251 et seq. 1972) established a long-term objective to restore and maintain chemical, physical, and biological integrity of aquatic resources. The CWA requires states, territories, and tribes (herein referred to as "jurisdictions") to adopt water quality standards as provisions of jurisdictional law or regulation (**Appendix D**). Water quality standards establish the water quality goals for all waters within their jurisdiction, including waters of the territorial seas and provide a regulatory basis when the water bodies do not meet their designated use(s). EPA works with state and territorial governments and other federal agencies to implement CWA programs and to protect coral reefs. EPA is a member of the USCRTF and partners with jurisdictions and other federal agencies to prevent land-based sources of pollution, such as stormwater, sediment, or sewage from impacting coral reefs and to develop water quality standards and criteria to protect their waterbodies.

In 2006, Aaron Hutchins, the Director of the USVI Department of Planning and Natural Resources (DPNR) requested assistance from EPA in developing protective measures for coral reef ecosystems, including information and guidance on the development of biological criteria for territorial water quality standards. In response, EPA's Office of Research and Development (ORD) began to develop coral reef biological indicators and assessment methods for coral reef ecosystems (Fisher 2007; Fisher et al. 2007, 2008; Fore et al. 2006a, b), including a 2006 coral reef survey in the USVI (Fisher et al. 2014) and testing indicators for responsiveness to anthropogenic stress as metrics that can be used in BCG rule development (Fisher et al. 2008). In September 2007, the EPA and USVI DPNR held a workshop in St. Croix, USVI to initiate a process to design an integrated monitoring program capable of meeting multiple management objectives (Bradley et al. 2014a).

Following the workshop, EPA ORD focused the Agency's coral reef research program on coral reef ecosystems in Florida, Puerto Rico, and the USVI (Bradley et al. unpublished). EPA conducted two probabilistic surveys of stony coral condition in the USVI: St. Croix in 2007, and the islands of St. Thomas and St. John in 2009 (Fisher et al. 2014). The same approach was applied in 2010 and 2011 on Puerto Rico reefs, including an expanded protocol that simultaneously assessed stony coral, fish, sponge, and gorgonian condition (Santavy et al. 2012;

Oliver et al. 2014; Fisher et al. 2019). Detailed descriptions of the methods and indicators are provided in Santavy et al. 2012.

In 2013, NOAA implemented the first year of its National Coral Reef Monitoring Program (NCRMP) in the USVI using a stratified random sampling design in shallow water coral reefs (0-30m). NOAA released the initial NCRMP guidance for the Caribbean in 2014 (NOAA 2014b, c, d), and regularly thereafter (NOAA 2015a, b, c, d; 2018a, b, c, d). NOAA and partners (UVI, NPS, University of Miami, TNC and USVI DPNR) monitored coral assemblage structure, benthic cover estimates for ecologically important cover types/groups (*e.g.,* macroalgae, turf algae, crustose coralline algae, corals, sponges, sand/sediment, etc.), rugosity, prevalence of bleaching, and measures of fish assemblage structure (abundance, diversity, size, etc.), mobile invertebrate counts (Caribbean spiny lobster (*Panulirus argus*), queen conch (*Aliger gigas*), long-spined sea urchins (*Diadema antillarum*)), and presence/absence of threatened and endangered species. In the Caribbean, there are seven scleractinian coral species and two fish species listed as threatened and no species listed as endangered. NMFS has the authority to use regulatory measures (e.g., impose limitations on activities such as collection) to protect corals listed under the Endangered Species Act (ESA) or managed as essential fish habitat. NOAA has issued recovery plans for the two ESA-listed Atlantic Acroporid species (NOAA 2015e) and has issued recovery outlines for the five other ESA-listed coral species and four fish species (NOAA 2020a, b)
.

EPA ORD and Office of Water (OW) held a workshop August 21-22, 2012 at the Caribbean Coral Reef Institute, Isla Magueyes, La Parguera, Puerto Rico on coral reef biological integrity that brought together scientists with expertise in coral reef taxonomic groups to begin development of a model that describes characteristics of the coral reef for each Level of the BCG (Bradley et al. 2014). The BCG Level definitions are standardized, but must be described for each dataset, thus calibrating the meaning of the BCG to the characteristics observed in the dataset. The experts individually rated each site as either very good, good, fair, or poor and documented their rationale. The group discussed the reef attributes that characterize biological integrity (or the natural condition) for Puerto Rico's coral reefs. The experts assembled a conceptual BCG based on stony corals, fishes, gorgonians, sponges, algae, large vertebrates (e.g., turtles), and mobile invertebrates for shallow-water linear reefs of southwestern Puerto Rico. The experts identified a suite of measurable attributes for each assemblage. The conceptual BCG had four distinct Levels of condition: very good – excellent, good, fair, and poor (**Figure 3**; Bradley et al. 2014). These were simplified descriptions of the six standardized BCG Levels that were ultimately used in model development.

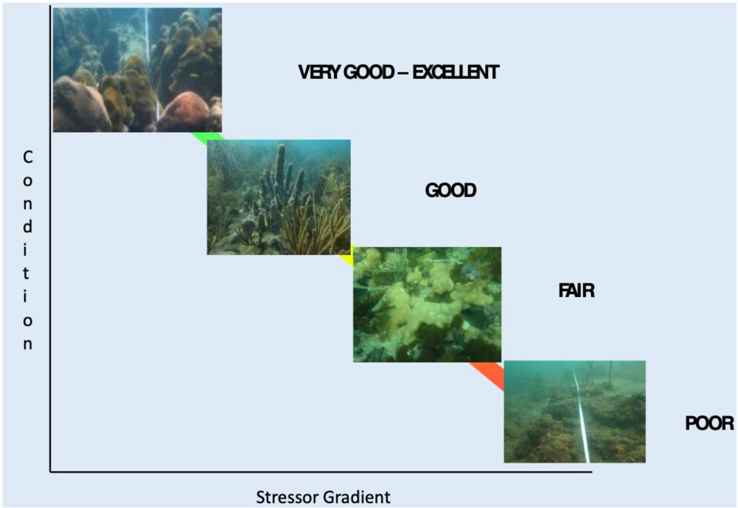


Figure 3. Conceptual Coral Reef BCG Model developed by experts in 2012.

Over the course of eight years, a committed workgroup of diverse coral reef experts met to refine the initial BCG calibration and to develop a predictive model of biological condition (**Appendix E**). The model incorporates the experts' interpretations of reef conditions relative to six standardized BCG Levels. (**Figure 1** and **Appendix C**). Sites from Puerto Rico, the USVI, and Florida were reviewed in a systematic process to develop the BCG model that operationalized the decision rationale so that the biological condition of new sites can be predicted based on bioassessment monitoring data.

BCG Model Development Outline

2012 Proof of Concept – Experts examined whole reef assemblages using EPA data and videos to categorize sites into Very Good, Good, Fair, and Poor biological conditions

2014 Narrative Model Development – Experts refined the Proof of Concept to formalize assemblage descriptions in terms of the BCG Levels. Experts split into groups to address fish separately from the benthic assemblage. BCG Attributes were assigned to fish and stony corals.

2015 Fish and Benthic Model Refinements – The benthic experts continued evaluating biological conditions in narrative terms, addressing reef classification. The fish experts drafted and validated a numeric model. The coral reef benthic model was revised to include algal metrics and other benthic components.

2019 Model Refinements – Benthic experts calibrated the numeric model using NOAA NCRMP data. Validation occurred during webinars. Fish experts tested the transferability of the BCG numeric model using data from the Florida Keys.

Description of the study area

Coral reefs differ in type and habitat across depth and geographic zones. For this project we focused on forereef coral ecosystems in Puerto Rico, the U.S. Virgin Islands (USVI) and Florida

(**Figure 4**) because: (1) they encompass the largest reef area; 2) they serve the greatest number of beneficiaries; (3) they are subject to Clean Water Act (CWA) jurisdiction, and (4) they were under the greatest environmental threats when we began the research (Burke and Maidens 2004).

Figure 4. Target jurisdictions for EPA Coral Project include Florida (Florida Keys and Southeast Florida reefs), Puerto Rico, and the U.S. Virgin Islands, including St. John, St. Thomas, and St. Croix.

Puerto Rico

Puerto Rico, the smallest of the Greater Antilles, is an archipelago composed of the main island; the oceanic islands of Mona, Monito, and Desecheo; Caja de Muertos Island on the south coast; Vieques Island; Culebra Island; and a series of smaller islets or cays known as the "Cordillera de Fajardo". The Commonwealth of Puerto Rico has an area of 5,320 square miles (13,800 km^2), of which 3,420 square miles (8,900 km^2) is land and 1,900 square miles (4,900 km^2) is water, with fringing coral reefs totaling 1,301 square miles (3,370 km^2) off the east, south and west coasts (Wilkinson 2004; Burke and Maidens 2004).

- The north and northwest coasts are subject to strong wave action during winter and receive substantial sediment and nutrient loading from the discharge of the largest rivers of Puerto Rico.
- The northeast coast, partially protected from wave action by a chain of emergent rock reefs (Cordillera de Fajardo) aligned east-west between the main island and the island of Culebra is upstream from the discharge of large rivers, resulting in waters with good transparency. Fringing reefs are found off the northeast coast at Rio Grande, Luquillo, Fajardo, Culebra, and Vieques.
- The east coast is characterized by extensive sand deposits with scattered rock formations that have been colonized by corals.
- Culebra is located approximately 17 miles (27 km) east of the Puerto Rican mainland, 12 miles (19 km) west of St. Thomas and 9 miles (14 km) north of Vieques. Culebra is an archipelago consisting of the large island and twenty-three smaller islands that lie off its coast. From 1939 to 1975 Culebra was used as a live-fire gunnery range for the USN.

Since 2011 the Department of Defense and its contractors have been conducting munitions cleanup of unexploded ordnance on the main island and offshore. Culebra's shoreline is marked by cliffs, sandy beaches, mangrove forests, and coral reefs.

- Vieques is located about ten miles (16 km) east of Puerto Rico with a land area of 52 square miles (130 km^2). In 1941 the USN purchased or seized about two thirds of Vieques, and after the war, the USN continued to use the island for military exercises and as a firing range and testing ground for munitions. The former USN lands, now a National Wildlife Refuge, occupy the entire eastern and western ends of Vieques, with the former live weapons testing site at the extreme eastern tip. These areas are unpopulated. The former civilian area occupies roughly the central third of the island. There are no permanent rivers or streams. Around the coast lie sandy beaches interspersed with lagoons, mangroves, salt flats, and coral reefs.
- The south coast of the main island of Puerto Rico has relatively low wave energy, a wide insular shelf, discharge from small rivers, a series of embayments and submarine canyons, seagrass beds and fringing mangroves, and small mangrove islets fringing the coast.
- Off the central west coast lies Mayaguez Bay, one of the largest estuarine systems of the island with coral reefs showing a marked trend of deterioration closer to the shore.
- North of Mayaguez is Rincón, where coral reef systems are established throughout the relatively narrow shelf off Tres Palmas, including an elkhorn coral (*Acropora palmata*) biotope fringing the coastline that is probably the largest remaining stand in Puerto Rico. A series of patch reefs are distributed throughout the Rincon mid-shelf, and there is a "spur-and-groove" coral reef formation at the shelf-edge.
- Off the northeast coast of Aguadilla, several small marginal shallow coral reefs are associated with rock outcrops. These are strongly affected by intermittent river discharge (Culebrinas River) and wave action. East of Aguadilla, the influence of large river plumes, a prominent feature of the coastline, constrains coral reef development, but hard ground and rock reefs with live corals are present throughout.
- Mona, Monito, and Desecheo are oceanic islands that are exposed to strong wave action, with coral reefs along their southern coasts. There are no rivers on any of the islands, which are surrounded by waters of exceptional transparency (Cintrón et al. 1975).

U.S. Virgin Islands

The U.S. Virgin Islands (USVI) are in the Leeward Islands of the Lesser Antilles to the east of Puerto Rico and west and south of the British Virgin Islands. The USVI includes the primary islands of St. Croix, St. John, and St. Thomas, as well as off-shore cays. The USVI totals roughly 347 km^2 of land area, 1,564 km^2 of water, and total reef area of 485 km^2 to a depth of 30 m (Kendall et al. 2001; Rogers et al. 2008).

- ***St. Croix*** is the largest of the three USVI islands at 215 km^2 is separated from St. Thomas and St. John by 55 km across the 4500-m deep Virgin Islands Trough. This island has coral growth along much of the insular shelf with a well-developed fringing reef on the eastern end, and deep coral walls including a submarine canyon on the north shore. St. Croix is the only island with a permanent source of freshwater. Buck Island Reef National Monument (National Park Service) is located on the northern portion of East End Marine Park in St. Croix. The Salt River Bay National Historical Park and Ecological Preserve is located on the north-central coast of St. Croix.

- ***St. Thomas*** is the second largest at 83 km^2 and St. John is the smallest of the three USVI islands at 52 km^2. ***St. John*** is largely incorporated into the Virgin Islands National Park (National Park Service), which covers all but the western coast of the island. Reefs in St. Thomas and St. John generally form fringing, patch, or spur and groove formations that are distributed irregularly around the islands.

Florida

Florida is the southern most of the 48 contiguous states, located at the convergence of the subtropical and temperate climate zones. Florida totals 65,757.70 sq. mi (170,312 km^2) of land area, with a 1,350 mi (2,170 km) coastline. The water boundary is three nautical miles (3.5 mi; 5.6 km) offshore in the Atlantic Ocean and nine nautical miles (10 mi; 17 km) offshore in the Gulf of Mexico.

Coral reefs in Florida occur along most of the Atlantic coastline and are easily separated into two different regions: Southeast Florida (north of Miami, including Martin, Palm Beach, Broward, and Miami-Dade counties) and the Florida Keys (south of Miami, consisting of Monroe County), which extend south and west into the Gulf of Mexico. Reefs at Dry Tortugas National Park represent the southwestern tip of the chain.

- Florida Keys. The Florida Keys is the only emergent coral reef ecosystem found off the continental United States. This marine habitat is under protection, with the extreme northern end as the Biscayne National Park managed by the NPS and the remainder of the reef tract managed by NOAA and the State of Florida as the Florida Keys National Marine Sanctuary (FKNMS), and Dry Tortugas National Park (managed by the NPS).

- Southeast Florida. The coastal region of SE Florida is highly developed, containing 43% of Florida's population of 21.8 million people (U.S. Census Bureau, 2019). Many SE Florida reefs are located just 1.5 km from this urbanized shoreline. SE Florida reefs are the northern extension of the Florida Keys that extend into a more temperate climate. Significant but more limited hard corals exist, including some of the largest staghorn coral patches throughout the Florida system. These communities diminish northward along Florida's coast. The importance of the southeast Florida reefs was recently recognized by the establishment of the Southeast Florida Coral Reef Ecosystem Conservation Area in 2018. Management of these reefs is through a consortium of local and regional agencies that form the Southeast Florida Coral Reef Initiative (SEFCRI) Team.

Steps to develop the BCG model for the Caribbean reef fish and benthic assemblages followed a series of steps described in technical guidance on the development of a BCG (EPA 2016). Constraints include the availability and consensus of fish and benthic assemblage experts, and the availability and applicability of sample data. The basic steps include, 1) the organization of sample data into interpretable presentations, 2) the orientation of the experts to BCG concepts and project objectives, 3) the assignment of BCG attributes to taxa, 4) an expert rating of biological samples from field surveys into BCG Levels, 5) the translation of sample ratings into narrative rules and responsive metric values into quantitative models, and 6) the validation of the models with independent data (**Figure 5**). Technical analysts facilitated and supported the experts. The analysts had thorough knowledge and experience with the BCG and were able to remain neutral on taxa attribute and sample Level assignments after describing the standard definitions and processes. Analysts also compiled, organized, and summarized data for review of taxa, samples, metrics, and draft models.

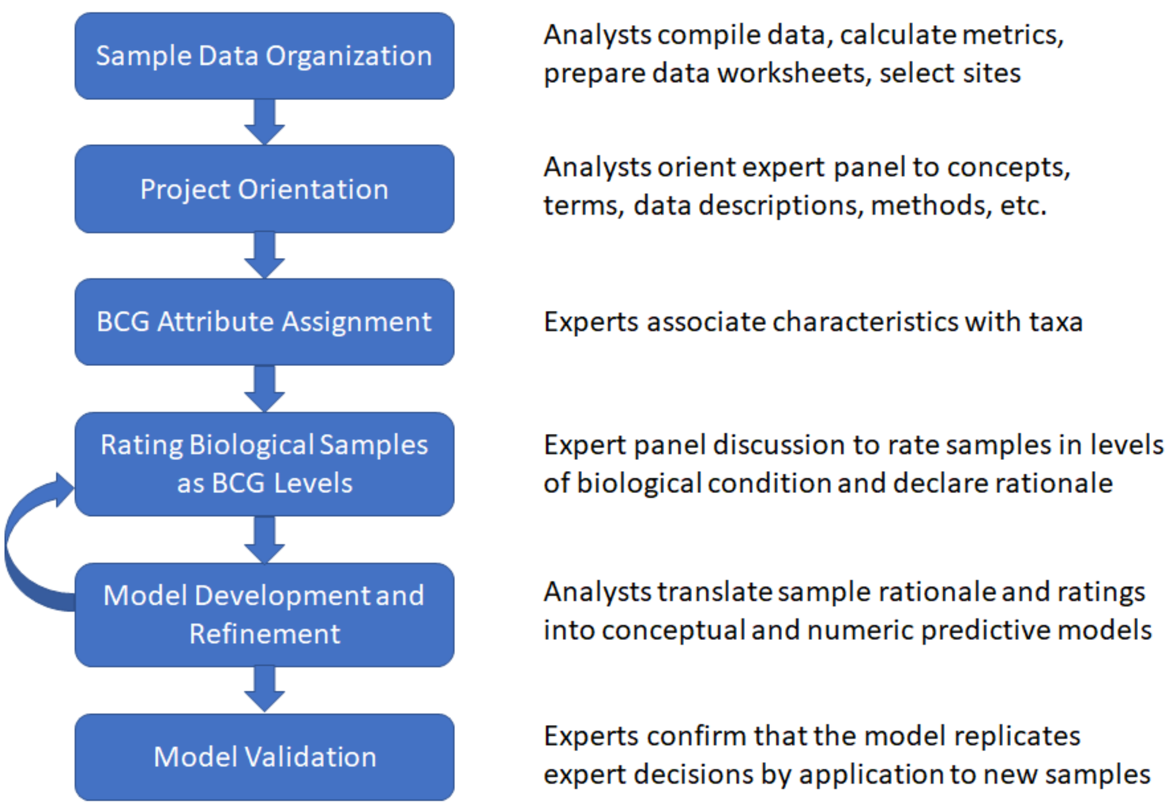


Figure 5. General process for development of the BCG model.

Data used in the development of the Coral Reef BCG Models

Three different data sets were used to develop the coral reef BCG models, which were used for different assemblages and steps of model development. A summary is provided in **Table 2**, and a full description of the data sets is provided below. Water quality data were not collected during these surveys. The field survey methods were observational and resulted in minimal impacts to the ecosystem.

Survey data were subjected to thorough QA/QC to eliminate uncorrectable, unmatched, or conflicting data, sites deemed to be in non-target habitat types, and to correct older taxonomic names or synonyms. The data were then put into an Excel workbook for use by the experts. The workbook included a series of linked worksheets:

- Notes, including descriptions of the other worksheets and metadata
- Status page, with a summary of sites and expert consensus BCG Level assignments
- A master table of taxonomic attributes and characteristics that provides species information, including scientific and common names, classification, BCG attribute, and assemblage-specific traits. For fish, these included trophic guild, whether large or small for important targeted species, preferred habitat (Humann and DeLoach 2003), and tolerance to sediment and fishing pressure. For the benthic assemblage, these included attributes for hard corals.
- A data habitat worksheet that provides other information by sample (e.g., exercise ID, collection date, collection method (EPA, NCRMP, RVC), region, latitude/longitude, survey year, reef type, whether in an MPA, habitat (NOAA benthic maps), etc). Data sheets from individual monitoring sites, including site and sample information, including assemblage-specific metrics.

EPA 2010/2011 surveys

EPA conducted two underwater coral reef surveys in 2010 and 2011 along the south coast of Puerto Rico to support the development of coral reef biocriteria and the BCG (Fisher et al. 2019). The EPA data were used for the proof of concept to demonstrate a conceptual BCG model for both fish and benthic assemblages. The EPA data were also used in development of narrative BCG rules for the benthic assemblage and for calibration and validation of the numeric fish BCG model. For completion of the numeric benthic model, the NOAA NCRMP data were used.

The EPA survey methodology was designed as an efficient, inexpensive, nondestructive method that generates useful indicators for management programs. This was particularly important because U.S. jurisdictions have limited resources for the monitoring and assessment needed to support CWA requirements. The surveys targeted scleractinian coral, fish, sponge, and gorgonian assemblages on linear coral reefs within 4.8 km of shore (including shores of small islands) at depths ≤ 12 m as characterized in NOAA's benthic habitat map (Kendall et al. 2001) for several reasons: 1) the shallow, near-shore environment can be readily accessed by small boats and is therefore efficient and safe for divers; 2) the near-shore environment maintains proximity to potential human disturbance in adjacent watersheds (Fisher 2007; Fisher et al. 2014); and 3) the literature shows a distinct difference in shallow and deep reef fish assemblage structure (Brokovich et al. 2008).

Table 2. Data Used in the Development of the Coral Reef BCG Benthic and Fish Models.

Data set	Brief Description	Application in BCG Development
EPA 2010 and 2011 surveys along the south coast of Puerto Rico	The surveys targeted scleractinian coral, fish, sponge, and gorgonian assemblages on linear coral reefs that occur on coral reef and hard bottom substrate as defined in the 2001 NOAA benthic habitat maps for southern Puerto Rico (Kendall et al. 2001). Surveys were conducted within 1.5 km from shore and to a maximum depth of 12m.	• Proof of Concept (narrative descriptions of 4 Levels of Coral Reef Condition) – using visual media only • Fish Model development – entire process • Benthic Model – narrative rule development only
NOAA National Coral Reef Monitoring Protocols (NCRMP) 2013-2015 surveys of Puerto Rico and the U.S. Virgin Islands	NCRMP targeted sessile benthic and fish assemblages in a stratified random sampling design, where the sampling domain for each region (*e.g.,* Puerto Rico, the USVI) was partitioned by habitat type and depth, sub-regional location (*e.g.,* along-shelf position), and management zone.	Benthic Model – numeric rules development and model validation
Fish surveys in Florida Keys and Dry Tortugas, 20142016	Reef Visual Census (RVC) for 14 sites from 2014-16 surveys in Florida Keys and Dry Tortugas, at depths shallower than 16 m.	To test the transferability of the BCG fish model from Puerto Rico and the USVI to another region (Florida)

The 2010 survey was designed to document coral reef impacts from land-based sources of sediment (i.e., terrigenous sediment) at 76 sites (Oliver et al. 2014, 2018; Bradley et al. 2014, 2020) (**Figure 6**). Risk of contamination by terrigenous sediment was based on the Reefs at Risk Program analyses (Burke and Maidens 2004), by which threat declines as distance from the threat increases. The benthic sediment threat (BST) is a compilation of watershed sources of sediment and pollution that incorporates erosion rates (slope, land cover type, precipitation, and soil type) and dispersion rates (hydrological dispersal in the coastal zone). The BST values were obtained for reef habitats which demonstrated the relative erosion potential for watersheds, adjusted for watershed size, and modeled to correspond with pour points (Oliver et al. 2018). The values and GIS platform were obtained from the World Resources Institute (WRI) and NOAA Summit to Sea model (WRI and NOAA 2006).

The 2011 survey sites were selected using a generalized random tessellation stratified approach (Stevens and Olsen 2004) for the 2011 survey (**Figure 7**). One objective of the project was to support development of a long-term monitoring program that could be used by Puerto Rico for

CWA reporting purposes. A second objective was to assemble a dataset that could be used for development of the BCG and ultimately, biocriteria (Fisher et al. 2019).

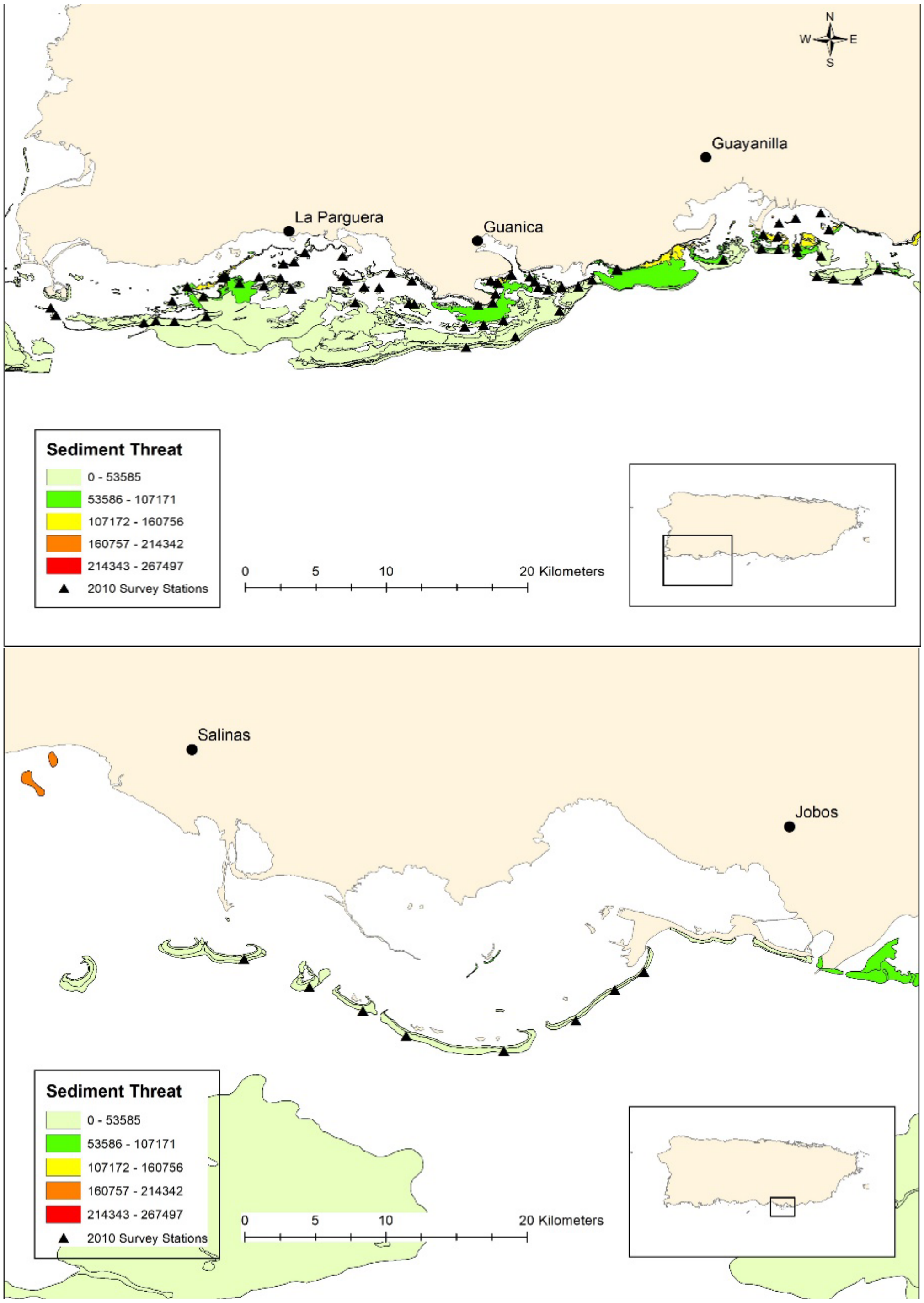
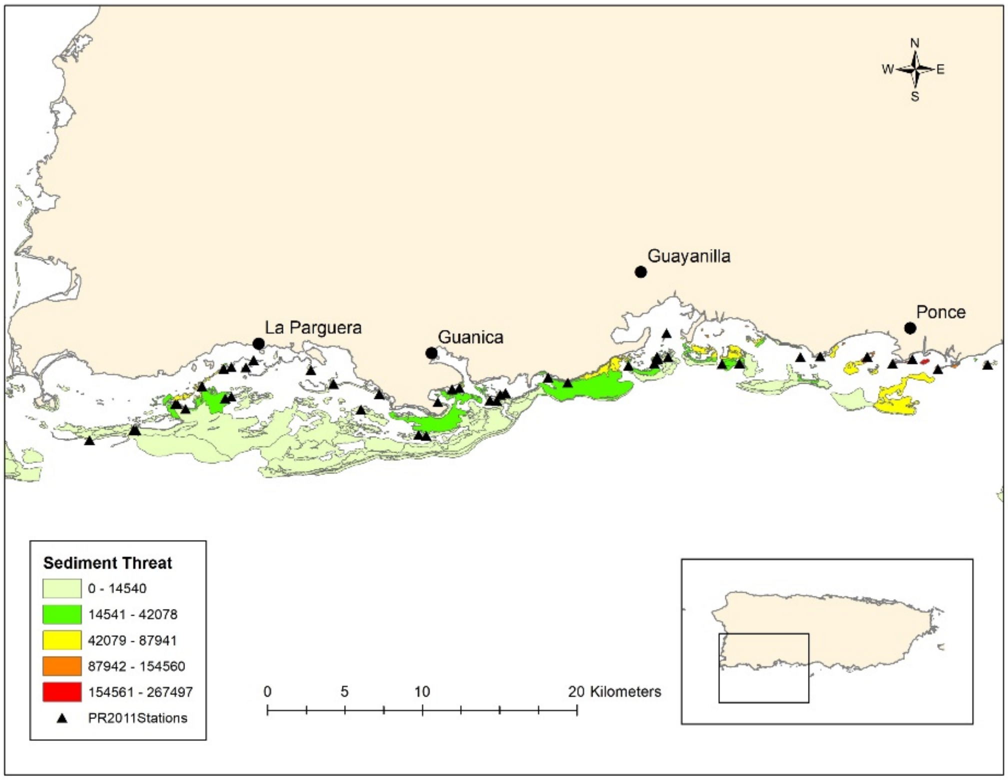


Figure 6. Location and Distribution of 2010 EPA Sampling Sites in Puerto Rico. Seventy-six targeted coral survey sites (black triangles) at regular intervals across human disturbance gradients were distributed across linear reefs within 1.5 km of shore (including cays) and between 2-12 m depth (Bradley et al. 2020).



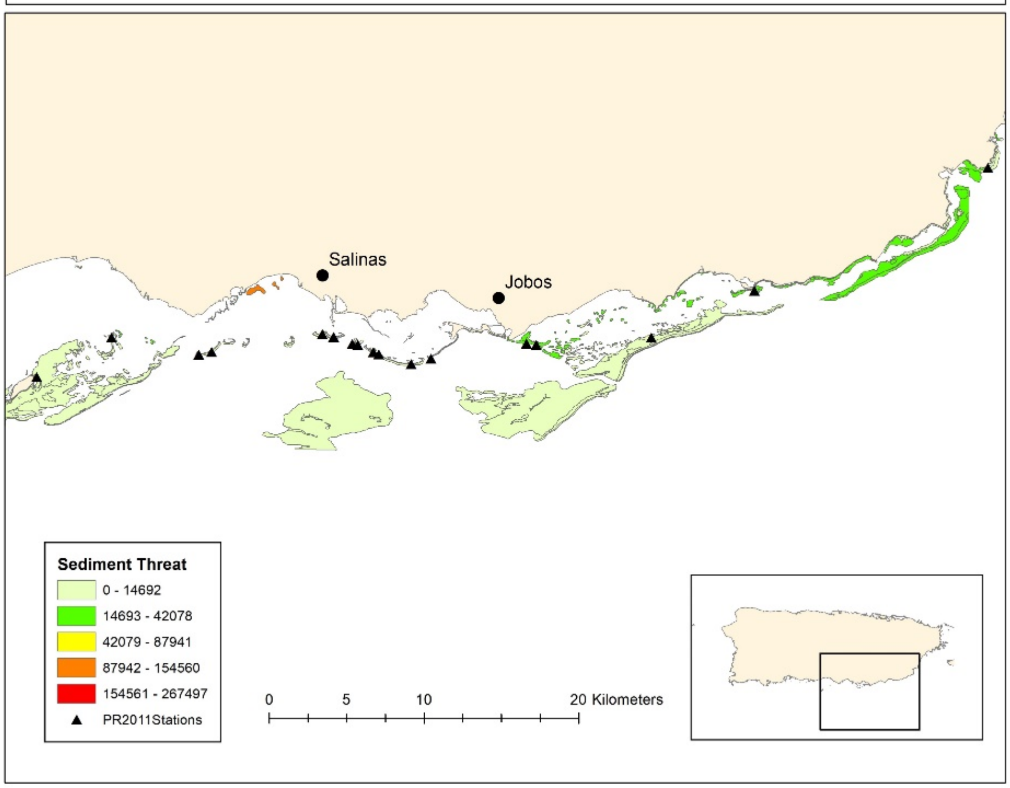


Figure 7. Location and Distribution of 2011 EPA Sampling Stations (Fisher et al. 2019). Sixty randomly selected coral survey locations (black triangles) were distributed across linear reefs within 1.5 km of shore (including cays in the target substrate).

EPA Coral Demographics Method.

The coral demographic (DEMO) method was used to observe and record hard coral condition . This method provided metrics for calculation of coral surface area, counts of taxa, and coral colony condition. A pair of divers swam along one 25m x 2m belt transect (**Figure 8**). One diver recorded the species, colony size, percent live tissue, and any disease or bleaching on all stony coral colonies found within 1 m of the tape (25m^2 stony coral transect area); while the other diver recorded the morphology (**Appendix F**) and size of all gorgonians and sponges found in five 1-m^2 quadrats along the other side of the tape at the 0, 5, 10, 15, and 20-m marks (a total 5m^2 transect area at each site for sponge and gorgonian census). The percent area covered by the zoanthid *Palythoa caribaeorum* was also recorded in the quadrats (Santavy et al. 2012; Fisher et al. 2019).

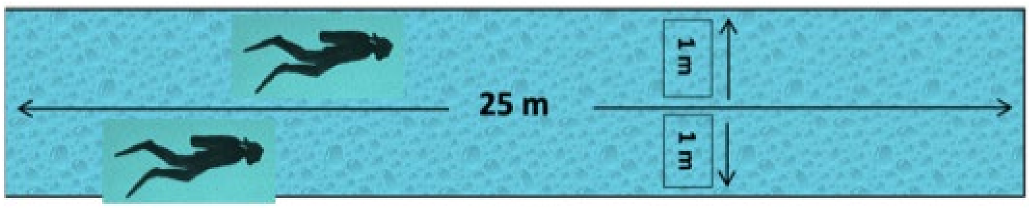


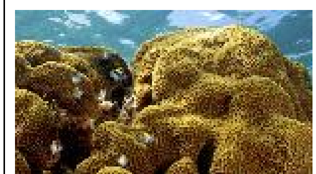
Figure 8. Two divers conducting the EPA DEMO survey. One diver is surveying stony corals on the right side of the transect and the other diver is surveying sponges and gorgonians on the left side of the transect.

The three measurements/observations recorded for each coral colony (species, size, and percent tissue area) allowed calculation of metrics reflecting aspects of assemblage composition, physical status, and biological condition of the colonies (Fisher 2007; Santavy et al. 2012). The sponge and gorgonian metrics provided estimates of the surface area contribution to reef habitat.

EPA Method to Identify Presence of Endangered/Threatened Species. Along the 25m transect, divers also recorded the presence of species listed under the ESA (**Table 3**). Threatened coral species included *Acropora cervicornis and Acropora palmata*. In 2014, NOAA listed five additional Caribbean coral species as threatened: *Dendrogyra cylindrus, Orbicella annularis, Orbicella faveolata, Orbicella franksi, and Mycetophyllia ferox* (50 CFR Part 223, 2014).

EPA Method to Record Mobile Invertebrates. The density of *Aliger gigas* (queen conch), *Panulirus argus* (spiny lobster), Scyllaridae (slipper lobster), and *Diadema antillarum* (long-spined black sea urchins) observed along the transect were recorded. Underwater videos were taken along the entire length of 25m transect and still photographs were taken to capture representative elements of the environment that might not have been reflected in the transect data. Only summary statistics of taxa richness were used for all other assemblages except scleractinian corals (Santavy et al. 2012).

Table 3. Caribbean scleractinian coral species listed as threatened under the endangered species act.

Scientific Name and Common Name	Photograph	*Scientific Name* and Common Name	Photograph
Acropora palmata Elkhorn coral		*Orbicella annularis* Lobed star coral	
Acropora cervicornis Staghorn coral		*Orbicella faveolata* Mountainous star coral	
Dendrogyra cylindrus Pillar coral		*Orbicella franksi* Boulder star coral	
Mycetophyllia ferox Rough cactus coral			

EPA Reef Rugosity Method. Reef rugosity (vertical relief and topographic complexity) was surveyed to infer topographical complexity of the coral reef surface. A rugosity index was applied as a reef-scale metric of reef contour or roughness (McCormick 1994; Alvarez-Filip *et al.* 2009) (**Figure 9**). For the 2010-2011 EPA surveys, rugosity was determined using a chain-transect method that compares the length of a chain draped along the contour of stony corals and non-coral substrate to the length of a taut line across the same linear distance. This generates a unitless value that can be used for relative comparisons across sites and reefs (Santavy et al. 2012).

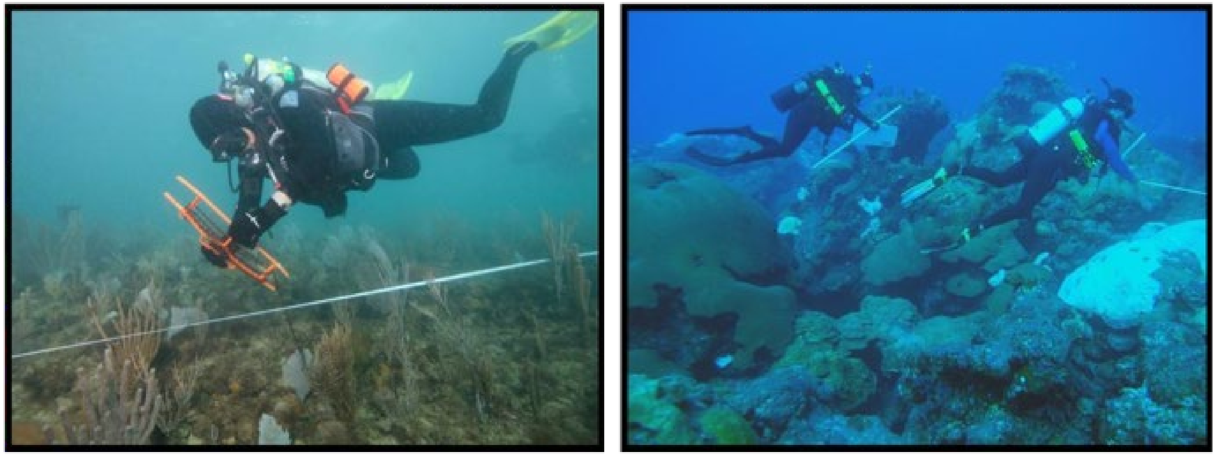


Figure 9. Examples of low rugosity (left) and high rugosity (right) reefs (source: Santavy et al. 2012).

EPA Fish Survey Method. Reef fish were surveyed visually to document the species, numbers, and sizes of all reef fishes along a single 25 m x 4 m underwater belt transect (100 m^2) and within the entire water column to the surface (**Figure 10**). Data were used to estimate abundance, species richness, and biomass for the fish populations, and subsequently classified by taxonomy and trophic guilds (Santavy et al. 2012).

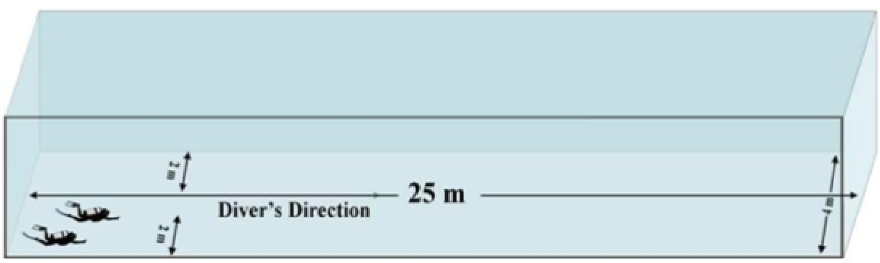


Figure 10. Diagram of fish transect using two divers in a 4 m x 25 m belt transect (100 m^2). All fish encountered in the water column or on the reef are included in the visual assessment. (source: Santavy et al. 2012).

Each fish was scored in 5cm size class increments up to 35cm using visual estimation of fork length (**Table 4**). For individuals greater than 35 cm, an estimate of the actual fork length was made. The fork length is measured from the snout (with closed mouth) to the fork at the base of the tail or caudal fin (**Figure 11**).

Table 4. Example fish data showing fish species and counts in length bins.

Species	Length (in centimeters)							
	<5	5-10	10-15	15-20	20-25	**25-30**	**30-35**	**>35**
Threespot Damselfish	1	19	9					
Yellowtail Snapper				2	1			
Spanish Hogfish			1		2			1 - 60
Stoplight Parrotfish						3	2	
Black Grouper								1 –72
Bar Jack			40	30	30			

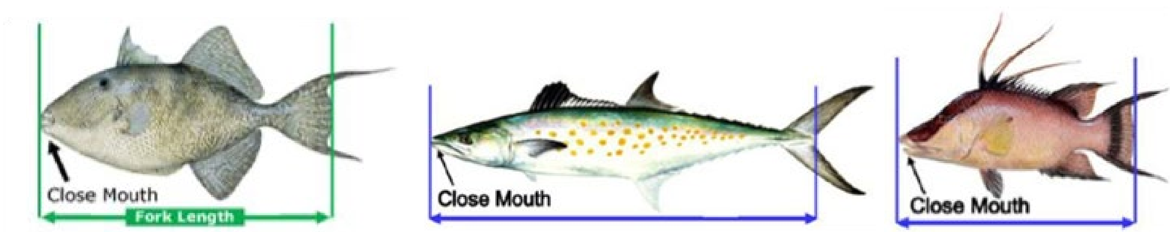


Figure 11. Fork length for different types of fish. The fork length is measured from the tip of the snout (with closed mouth) to the base of the caudal fin. (source: Santavy et al. 2012).

NOAA NCRMP surveys

Bioassessment data from NOAA's NCRMP Puerto Rico and the U.S. Virgin Islands surveys collected in 2013 – 2015 were used for developing the numeric benthic rules. NCRMP data quality is optimized by stratifying using combinations of depth (e.g., shallow, medium, deep), reef zone (forereef, backreef, etc.), habitat type (e.g., spur and groove, colonized pavement), and management zone (e.g., MPA, no-take area, etc.).

Although several NCRMP protocols were similar to those described for the EPA Puerto Rico data, there are some significant differences (detailed below). For example, EPA did not estimate the benthic coverage by other sessile benthic assemblages (algal taxa, exposed substrate, sponges, gorgonians, etc.), NOAA did not include sponge and gorgonian measurements in the DEMO surveys, NOAA used a microheterogeneity approach for reef rugosity, and NOAA sampled to 100-foot depths. The experts recognized natural differences in benthic reef assemblages inhabiting shallow and deep sites (Aguilar-Perera and Appeldoorn 2008; Smith et al. 2010; Andradi-Brown et al. 2016; Baker et al. 2016; Kahng et al. 2010; Rocha et al. 2018). The deepest sites in the data set were approximately 100 feet deep, which NOAA considers the maximum practical depth for routine underwater monitoring. Within this depth range, the experts suggested that differences in reef structure occurred at approximately 40 feet deep, as a result of gradual and general differences in light penetration and wave action. There was an effort to concentrate on shallow reef sites (<40 ft). However, a fuller range of BCG condition levels was found when including both shallow and deep sites for the benthic model. In addition, more samples were collected from deeper sites. Therefore, the reviewed benthic samples were from all depths (up to 100 ft). Differences in natural expectations and assessment results relative to depth were assessed during and after the BCG rating and prediction processes.

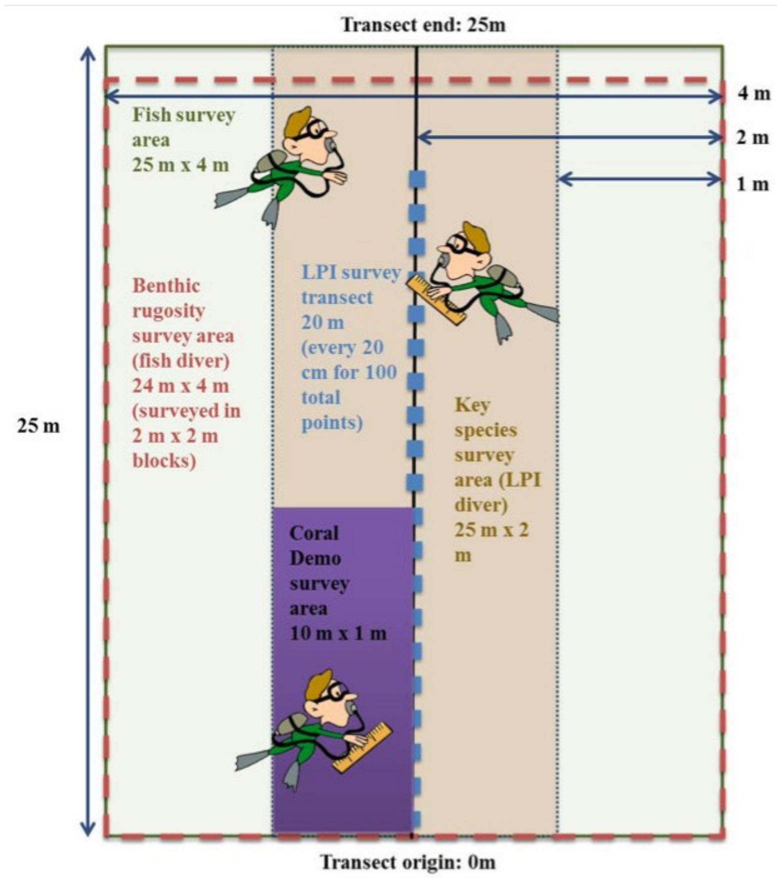


Figure 12. Diagram of NCRMP surveys (NOAA 2015a). Size of each respective survey area is also indicated. Fish, LPI, and Coral Demographics were surveyed as the divers moved away from the transect origin. Mobile invertebrates (e.g., spiny lobster, queen conch, Diadema urchins) and topographic complexity were surveyed as the divers returned to the transect origin.

NOAA NCRMP Line-Point Intercept (LPI) Method. NOAA employed the Line-Point Intercept (LPI) method to estimate the percent benthic cover of ecologically important cover types (macroalgae, turf algae, crustose coralline algae, corals, sponges, sand/sediment, etc.) (**Figure 12**). This method used points along a single 25m transect to quantify each of the benthic organisms or substrate types present lying every 20cm under the tape, a total of 100 points documenting the substrates and biota. Because the intervals were 100th of the transect length, each point constituted 1% of cover.

Along a 2m width of the 25m transect, divers conducted a survey for Key Species (ESA-listed species and selected mobile invertebrates), as described above (**Table 3**). The densities of *Aliger gigas* (queen conch), *Panulirus argus* (spiny lobster), Scyllaridae (slipper lobster), and *Diadema antillarum* (sea urchins) were recorded (Santavy et al. 2012). No underwater videos were taken. Underwater photographs were taken along the entire length of 25m transect (6-7 photos per survey).

NOAA NCRMP Microheterogeneity Measure. The NCRMP 2013-2015 surveys used a microheterogeneity measure to estimate reef rugosity. This measure was the calculated difference between the lowest and highest vertical heights in quadrats along the transect, averaged for all sampled quadrats at a site. Maximum hard bottom relief was measured at 24 locations along the 25m LPI transect, recorded as centimeters, and binned into six height classes (<0.2m, 0.2-<0.5m, 0.5-<1.0m, 1.0-<1.5m, 1.5-<2.0m, >2m). Using the frequencies from each transect, a single rugosity index was calculated. The frequency of each height class was used as the midpoint of each height class (lowest to highest: 0.1, 0.35, 0.75, 1.25, 1.75, actual height if >2m) multiplied by the number of observations in that height class. If the height was >2m, the maximum vertical height was the multiplier. Finally, the sum of the products from all height classes was divided by the total number of observations (24) to obtain the microheterogeneity rugosity value (MRV) (NOAA 2014d). The maximum and minimum transect depths were noted (Brandt et al. 2009).

NOAA NCRMP Coral Demographic Method. The DEMO surveys were conducted at a subset of LPI sample sites (2013: 220 DEMO surveys/283 total surveys; 2014: 111/230; 2015: 139/239). Divers swam along a single 10m x 1m belt transect, recording information on coral species composition, size, abundance, and specific parameters of condition (% live vs. dead and bleaching; presence/absence of disease) of non-juvenile scleractinian corals (> 4cm maximum diameter), (**Figure 12**). From the species, size, and condition measures of the DEMO surveys, coral surface area (CSA) and live coral surface area (LCSA) were calculated in two and three dimensions (**Appendix G**).

Florida Reef Visual Census (RVC)

The 4th BCG workshop focused on potential transferability of the Puerto Rico fish model to a different jurisdiction (Florida). Experts rated 14 sites in the Florida Keys and Dry Tortugas at depths shallower than 16 m, which were co-sampled by both the fish and benthic teams (Bohnsack and Bannerot, 1986). The sites were selected by the RVC leads across a stressor gradient: water quality (low anthropogenic impact – Dry Tortugas, low-moderate impact – Florida Keys forereef, and high impact – Hawk’s Channel); and fishing pressure based upon management zones (low – Dry Tortugas National Park; medium – Florida Keys, Marine Protected Areas; and high – Florida Keys outside of Marine Protected Areas).

The Florida Reef Visual Census (RVC) method has been used to survey reef fish populations along the Florida reef tract in a variety of benthic habitat types, ecoregions, and management areas (Brandt et al. 2009; Kilfoyle et al. 2017). This method collects information on the density and size distributions of the fish assemblage (except for cryptic species), as well as information on benthic habitat features.

The RVC uses a two-stage stratified random sampling design. The Florida Keys and Dry Tortugas sampling domains are partitioned into 200 x 200 m grid cells (the primary units), which are each assigned to a strata designation based on habitat type, geographic sub-region, management type (open vs. closed to fishing), and depth. Primary units to be sampled are then randomly selected from a list of all possible primary units for each stratum. Within each selected primary unit, two smaller units (the second stage) are haphazardly selected. Each second-stage unit consists of a pair of divers who each perform a Reef Visual Census (RVC) which is a 15 m diameter stationary point count (Bohnsack and Bannerot 1986; **Figure 13**). A comparability study between the stationary point count method and the transect method conducted in 1999-2000 determined that the stationary point count method was most successful at estimating fish species densities in Florida and has been employed annually in the Florida Keys ever since (Colvocoresses and Acosta 2007).

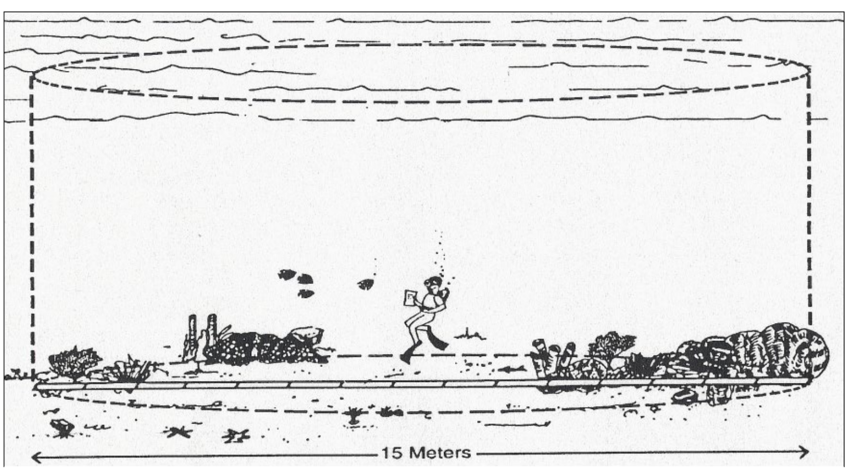


Figure 13. Conceptual diagram of Reef Visual Census (RVC) diver within 7.5 m-radius survey cylinder (from Rogers et al. 1994, based on Bohnsack and Bannerot 1986).

It is important to note that underwater visual census techniques (stationary point counts or belt transects) have biases that affect the accuracy of density estimates, in particular crevice-dwelling, cryptic, very secretive and nocturnal species (Bohnsack and Bannerot 1986; Ackerman and Bellwood 2000; Stewart and Beukers 2000; Willis 2001; Bozec et al. 2011). Very intensive sampling would be needed to detect these types of species (Bohnsack and Bannerot 1986).

Convening the Experts

An important component of the BCG process is the establishment of a panel of experts familiar with the taxonomy and ecology of coral reef aquatic biota. The experts' primary task is to make biological assessments of environmental conditions and to relate them to the BCG model (EPA 2016). In general, experts have been highly concordant in their ratings of sites for several different ecosystems, including marine benthic invertebrate communities in California bays (Weisberg et al. 2008), marine coastal benthic communities from four widely separated geographic regions (Teixeira et al. 2010), fish communities in a South African estuary (Harrison and Whitfield 2004), and a river ecosystem in Australia (Davies et al. 2010). In development of freshwater BCGs, experts have come to a strong consensus on the descriptions of individual BCG Levels and very close agreement on the BCG Levels assigned to individual sites (EPA 2016; Gerritsen et al. 2017).

A panel of coral reef experts was assembled in 2012 (Bradley et al. 2014b; Santavy et al. 2016; Bradley et al. 2020). Experts were chosen based on their scientific expertise in Caribbean coral reef taxonomic groups (e.g., stony corals, fishes, sponges, gorgonians, algae, seagrasses and mobile invertebrates), and overall coral reef ecology. Experts included research scientists from federal and state organizations, academia, and non-governmental organizations (NGOs), as well as water quality managers and natural resource managers from Puerto Rico and the USVI. A list of the BCG experts is available in Bradley et al. 2016 and **Appendix H**. The expert panel had few retirements and replacements over the course of the project. During the workshops, coral reef managers observed the expert deliberations, while the BCG technical team facilitated the process (**Appendices I and J**).

The BCG concepts and terminology were unfamiliar to most on the expert panel. The BCG had not previously been applied in tropical reefs, and the data interpretation was complex. Due to this fact, the orientation steps of the process were iterated until the understanding and calibration of the BCG model was completed.

Assignment of BCG Attributes to Fish and Stony Coral Species

To complement data interpretation, the taxonomic components (fish and stony coral) were associated with one of six BCG attribute categories that represented degree of sensitivity to pollution (I-V) and non-native taxa (VI). During the BCG model development, expert panelists consistently used these categories, and metrics based on these categories, to summarize shared characteristics among taxa. Many expert panelists (in particular, the fish experts) found these categories useful in addition to taxa lists in their analysis of site data.

Rating Biological Sites at BCG Levels

In early workshops and web-assisted conferences, the basic ideas of reef assessment were discussed without reliance on BCG terminology. This was done to facilitate expert sharing of knowledge and understanding of how coral reef biota respond to stress without getting distracted by new and unfamiliar terminology. Once a conceptual gradient of biotic response to stress was defined by the expert panel, BCG terminology was introduced and was readily understood and accepted.

Early meetings established a conceptual model that was later used to tailor the process and define data requirements for assessing the biological condition of coral reefs. Using this approach, the group formulated expectations for all condition Levels defined in the BCG framework by employing reef taxa and biological characteristics to align with the structural and functional descriptions for each BCG Level generic description. In the next rounds of BCG calibration, the expert panel broke out into two different assemblage groups; benthic and fish assemblages. Each assemblage had differences in sampling programs, sites, and methods, as well as in data availability and treatments, as described above.

Experts were asked to assign BCG Levels to sites based on their interpretation of taxa lists, assemblage metrics, and site information (**Figure 14**). The experts then provided their logic for assigning BCG Levels to sites. This expert logic was critical to the development of the BCG model with the aim of answering the questions – which information in the data set was ecologically meaningful to the experts? And why? Each expert assessed the site data individually, recorded their individual interpretation and rationale, and then, through a facilitated process, shared their ratings and logic with the full panel. Through discussion and further testing, the panel developed a consensus recommendation on a set of narrative decision rules.

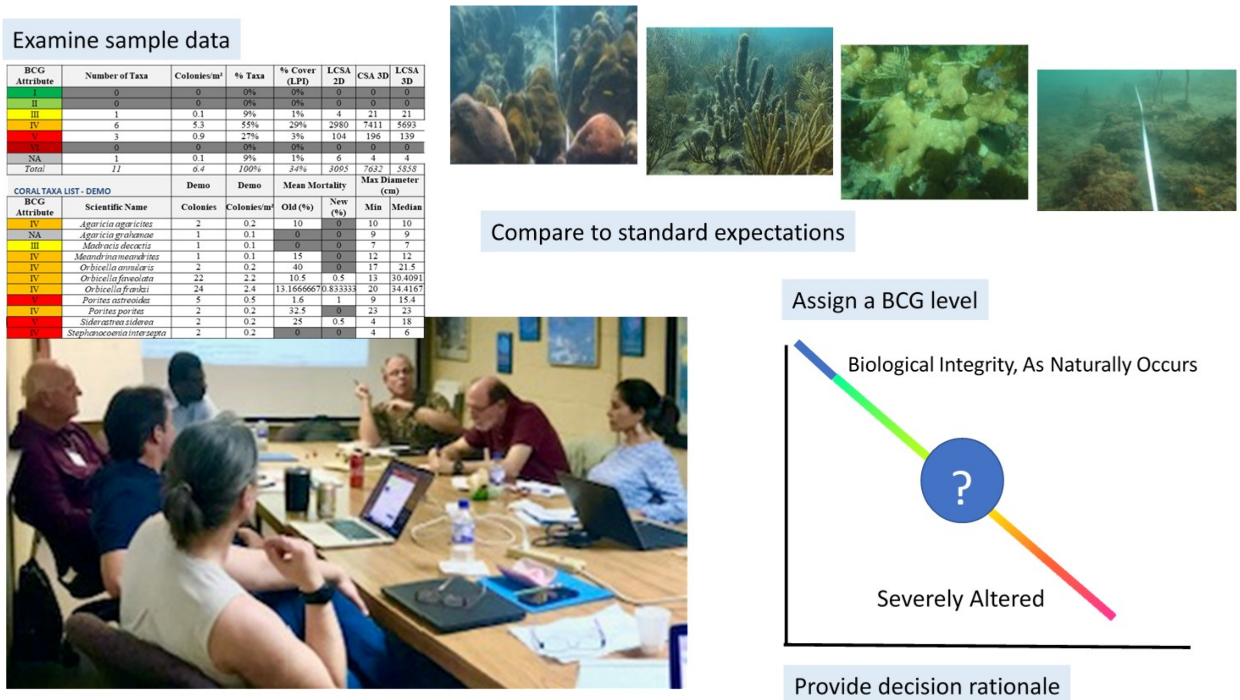


Figure 14. Illustration of the sample review and rating process, showing the expert panel reviewing the sample data, comparing sample characteristics to standard expectations for BCG Levels, assigning a BCG Level, and providing rationale for the BCG Level assignment.

The experts reviewed, discussed, and evaluated site characteristics and assemblage metrics for indications of biological condition. The expert panel members decided first individually, then as a group, which BCG Level best represented the biological conditions at a site. The experts then expressed the decision criteria as narrative statements relating metrics to the standardized BCG Level descriptions. The experts converted the sample BCG Level assignments (ratings) and rationale into narrative rules.

Decision rationales expressed by panelists usually included a statement about the critical components of the sample, such as overall taxa richness, organism density, taxa that indicated stress or lack thereof, trophic structure, organism condition, biomass, and other measurable metrics (**Table 5**). While experts were asked to provide an integer rating for the BCG Levels, they were sometimes unwilling to do so, and intermediate Levels were assigned as '+' (exhibiting characteristic of the next best conditions but not enough to rank the site in the better Level), and '-' (exhibiting characteristics that suggest somewhat worse conditions but not enough to rank the site in the corresponding worse (i.e. more highly degraded) Level). For example, a site was rated "4+" because the site was a very good "4" but not as good as a "3". In each case, the expert provided their logic for the "+" or "-" rating. This decision logic was extremely important information that indicated what shifts in the assemblage structure and function signaled that a site was approaching another BCG Level. Articulating these change-points and uncertainties allowed incorporation of ecologically meaningful decision rules in the BCG model.

Whether site reviews were conducted as a group during in-person meetings or web-assisted conferences, experts would first individually rate the site. When working individually on homework assignments, experts would write out their rationale. In both review settings, the resulting ratings and rationales would be compiled and discussed by the group at the workshop or a webinar. The median score was proposed as the site rating, and experts were asked to concur in a final rating for the site. This resulted in a BCG Level assignment that was agreed upon by consensus.

Table 5. Hypothetical example of expert ratings and rationales for a single benthic reef sample with summary rating of BCG Level 3.

Expert	Rating	Rationale
Expert #1	3+	Good live cover, good sizes, no new mortality, good fish diversity. Slightly better than a Level 3.
Expert #2	3-	Pro: cover, large colonies, no disease, or new mortality; Con: low sensitive taxa, high old mortality. Not quite a Level 3.
Expert #3	3-	Mid depth surmising forereef terrace. Lots of small coral colonies and a few larger colonies of *Orbicella*; not that much partial mortality. Coral cover in the model range for Level 3. Algae cover not that high. Few sponges and gorgonians. More or less expected for mid-depth terraces except coral cover should be higher.
Expert #4	4	Low density and only 1 attribute III taxon; a few large colonies but high mortality, indicating good conditions gone bad
Expert #5	2-	Best site we have seen but does not meet Level 2 because of coral mortality.
Expert #6	3-	Moderate coral cover but mostly small colonies. moderate turf algae %

The review process would continue until adequate numbers of sites were rated for the model development stage. Ideally, 20 sites per BCG Level would be evaluated so that characteristics of each Level could be distinguished with some degree of robustness. However, this number of sites was not always attained due to a lack of valid sites or sites covering all BCG Levels. For example, there were no undisturbed or minimally disturbed sites available. The BCG Level 1 was defined narratively to provide context and the quantitative model was derived to identify sites that range in condition from BCG Level 2 to Level 6.

Rule Development and Refinement

The technical analysts interpreted the narrative rules as numeric sample metrics based on available data. Over 100 metrics for each assemblage were calculated to address the narrative rules and variations. The metrics were presented to the expert panel, showing boxplots of metric distributions among sample BCG ratings. The experts selected metrics that represented the narrative intent as candidates for the model. The visual evaluation of the distributions was sufficient to illustrate general patterns of metric response that supported, partially supported, or refuted expectations described in the narrative rules. The experts usually eliminated metrics that did not distinguish between levels because they would not improve model results. However, with expert consent these unresponsive metrics could be included because they truly represented the narrative rules.

The analysts then drafted numeric rules and combinations of rules to produce a model with measurable predictive accuracy, where the model predicted the same Level as assigned by the experts. Each model includes a cascade of rules for membership at each BCG Level, starting with conceptual rules for Level 2 and proceeding with testable rules for Levels 3 through 5. Samples that failed at all Levels automatically were evaluated as Level 6. The analysts attempted to use several responsive metrics selected by the experts, meaningful thresholds provided by the experts or detected in the metric distributions, and logical combinations to maximize model performance. The draft model was iteratively applied, presented, reviewed, and revised until the expert panel agreed that the model replicated their decision processes and accurately predicted each BCG Level they assigned through consensus.

Development of the Predictive BCG Decision Model

To allow for consistent assignments of sites to BCG Levels, it was necessary to formalize and quantify the expert knowledge by codifying Level descriptions into a set of quantitative rules (e.g., Droesen 1996). Rules are logical statements that the experts used to make their decisions on BCG Levels. Once the rules have been quantified, it is expected that a knowledgeable person can follow them to obtain the same BCG Level ratings as the group of experts, allowing the decision criteria to be transparent for water quality managers and stakeholders. Rules can be nonlinear or non-monotonic and are robust to missing information.

The process of rule quantification was guided by the narrative descriptions of sample characteristics at each BCG Level, by any quantitative thresholds or observations expressed by the experts, and by distributions of measurable site characteristics corresponding to the descriptions (especially box-plots of metric distributions in sites at each rated Level). When the metric patterns in the visually assessed boxplots matched the expert narrative statements, then the metric was considered a good candidate for the model. If the metric patterns did not match the narrative statements, then several explanations were possible. These explanations include metrics responding to natural factors that were not recognized, inconsistent rating by individual experts or the entire panel, or metrics that did not represent the narrative rule as originally intended. There also could be confounding or compounding factors that were not recognized, were not stated, or were not discernible in the data set. When these situations occurred, the expert panel was consulted and their evaluation and hypothesis for discrepancy recorded. An expert panel recommendation was solicited for future work to address any discrepancies.

An example of a narrative rule that was not supported in the data regards rugosity. High rugosity was expected by the expert panelists to indicate natural or close to natural reef biological conditions. The experts stated this expectation as a narrative rule when reviewing both benthic and fish site data. However, rugosity as measured by either of two methods did not discriminate among the BCG Levels. Because of this unexpected lack of corroboration, the experts recommended reconsideration of how rugosity is measured (as discussed in the Summary and Recommendations for Future Research section). The rugosity measure was not used in the BCG benthic model even though the narrative rule was expressed, and the data were available.

Numeric model rules were expressed as a range of possible values that were expected for assemblage metrics at a certain BCG Level (EPA 2016; Bradley et al. 2020). The range of values acknowledges that there is uncertainty around the quantitative thresholds for the metrics, as expressed in the experts' narrative rationale. For example, a fish rule for Level 3 is: fish taxa ≥ 15 (10 - 20) taxa. Whereas the nominal value for the rule is 15, if the sample has fewer than 10 taxa, it is not at all like a Level 3, and if it has 20 taxa, it is similar to a Level 3 with respect to the number of taxa (see **Appendix K** for more detailed explanation of rule derivation). The rule thresholds were derived after multiple samples were rated and rationale for those samples were stated in relation to each metric. The numeric thresholds were first determined from the range of observed metric values compared among the assigned levels and any stated numeric values stated by the experts.

The uncertainty associated with the metric rule was apparent when sites with different metric values were assigned to the same level and the same narrative rational was expressed even though the metric values differed among samples. For example, an expert rationale for assigning a sample to a Level might be 'high live coral coverage' for two samples assigned to the same Level though the live coral coverage might be 20% in one sample and 30% in the other. The rule thresholds (nominal central value and ranges) were drafted using the empirical evidence from the metric distributions per assigned level. The ranges were centered on the nominal value to accommodate a linear interpolation of membership for the level. After being drafted for each responsive metric, each rule was presented to the expert panel, which decided to keep the rule, reject it, or modify some part of it (metric calculation or thresholds).

To characterize the dynamic and multifaceted nature of a biotic assemblage, the BCG model is comprised of a set of decision rules for each BCG Level that include an "and" for those rules that are always expected to be met and an "or" for combination of rules that capture the shifts and variability in an assemblage. The experts determined how the rules for each Level were to be applied: (1) all rules must be met, (2) some number of rules for that Level must be met, or (3) some rules can override results of other rules (EPA 2016). After formulating the rules, rule thresholds, and combination rules, the model was presented to the expert panel for approval or adjustment.

Results

Conceptual Model

Development of the Coral Reef BCG Framework

In a facilitated workshop held in 2012 at the Caribbean Coral Reef Institute, Isla Magueyes, La Parguera, Puerto Rico, the experts evaluated photos and videos for 12 sites collected during EPA surveys (2010 and 2011) from Puerto Rico coral reefs exhibiting a wide range of conditions. The experts individually rated each site as to observed condition (good, fair, or poor) based on videos and photos and documented their rationales for the assignments (**Figure 15**). At this stage in the process, benthic and fish experts collaborated in a single panel.

Figure 15. Photos from EPA coral reef sites reflect a range of coral reef conditions, from good (left) to intermediate quality (middle), to severely degraded (right).

The group discussed the reef attributes that characterize BCG Level 1: biological integrity (or the natural condition) for Puerto Rico's coral reefs, that served as the baseline condition, because CWA is grounded in the concept of natural, undisturbed conditions. Preliminary attributes were identified that would characterize a reef with excellent condition (undisturbed by anthropogenic stress) and that would serve as the reference condition for biological integrity. The concept of reference condition for biological integrity anchors the highest quality Level of the BCG, to aid in the interpretation of results when considering shifting baselines (Pauly 1995; Stoddard et al. 2006), and to help identify biotic changes resulting from historic pressures, as well as gradual regional or global stresses such as climate change. Furthermore, a concise description of reference condition in terms of biological integrity provides a basis for effective public communication of changes over time.

The experts agreed that there were no longer any reefs in Puerto Rico that met the BCG Level 1 definition corresponding to very good-excellent condition (Bradley et al. 2014b, 2020; EPA 2016). A BCG Level 1 condition was never observed and since underwater observations were not possible until substantial human disturbance was ubiquitous in the Caribbean (Jackson et al. 1997), the experts were not able to develop quantifiable rules for BCG Level 1. Experts shared videos and pictures of reefs from the MesoAmerican Reef that they believed exhibited full biological integrity (McField and Kramer 2007).

Using only the 12 sites, the experts developed a narrative framework to assess the biological condition for the forereef zone (i.e., the area along the seaward edge of the reef crest that slopes into deeper water on the barrier or fringing reef type; Costa et al. 2013) of shallow-water linear reefs of southwestern Puerto Rico based on physical structure of the reef, scleractinian corals and their condition, fishes, gorgonians, sponges, large vertebrates, algae, seagrasses, and mobile invertebrates. This approach resulted in attributes that were largely species-based (e.g., species diversity, apex predators), with notable additions (e.g., physical structure, organism condition). The experts identified four condition states: very good, good, fair, and poor; each with a consistent well-defined narrative (**Table 6**). As expected, no sites were rated as very good; however, the experts conceptualized the attributes for this Level, based on expert technical expectations.

The workshop provided proof of concept that the BCG can be adapted for coral reef ecosystems. The four condition levels represent BCG Levels. There were recognizable differences between levels that the experts could collectively describe with narrative statements of biological integrity that could be interpreted numerically, given appropriate survey data. EPA published a report (Bradley et al. 2014b) that provides a detailed summary of the workshop.

Table 6. Descriptions of four condition categories (very good to poor) based on expert assessments of individual sites (Bradley et al. 2014b). Continued on following pages.

Physical structure:	Very Good	High rugosity or 3D structure; substantial reef built above bedrock; many irregular surfaces provide habitat for fish; very clear water; no sediment, flocs, or films
	Good	Moderate to high rugosity; moderate reef built above bedrock; some irregular cover for fish habitat; water slightly turbid; low sediment, flocs, or films on substrate
	Fair	Low rugosity: limited reef built above bedrock; erosion of reef structure obvious; water turbid; more sediment accumulation, flocs and films; *Acropora* usually gone or present as rubble for recruitment substrate
	Poor	Very low rugosity: no or little reef built above bedrock; no or low relief for fish habitat; very turbid water; thick sediment film and thick floc covering bottom; no substrate for recruits
Corals:	Very Good	High species diversity including rare; large old colonies (*Orbicella*) with high tissue coverage; balanced population structure (old and middle-sized colonies, recruits); *Acropora* thickets present

	Good	Moderate coral diversity; large old colonies (*Orbicella*) with some tissue loss; varied population structure (usually old colonies, few middle aged and some recruits); *Acropora* thickets may be present; rare species absent
	Fair	Reduced coral diversity; emergence of tolerant species, few, or no living, large old colonies (*Orbicella*); *Acropora* thickets gone, large remnants mostly dead with long uncropped turf algae
	Poor	Absence of colonies, those present are small; only highly tolerant species with little or no live tissue
Gorgonians:	Very Good	Gorgonians present but subdominant to corals
	Good	Gorgonians more abundant than Levels 1–2
	Fair	Gorgonians more abundant than Levels 1–3, replacing sensitive coral and sponge species
	Poor	Small and sparse colonies; mostly small sea fans; often diseased
Sponges:	Very Good	Large autotrophic and highly sensitive sponges abundant
	Good	Autotrophic species present but highly sensitive species missing
	Fair	Mostly heterotrophic tolerant species and clionids
	Poor	Heterotrophic sponges buried deep in sediment; highly tolerant species
Fish:	Very Good	Populations have balanced species abundances, sizes, and trophic interactions
	Good	Decline of large apex predators (e.g., groupers, snappers) noticeable; small reef fishes more abundant
	Fair	Absence of small reef fishes (mostly Damselfish remain)
	Poor	No large fishes; only a few tolerant species remain; lack of multiple trophic levels
Large vertebrates:	Very Good	Large, long-lived species present and diverse (turtles, eels, sharks)
	Good	Large, long-lived species locally extirpated (turtles, eels)
	Fair	Large, long-lived species locally extirpated (turtles, eels)
	Poor	Usually devoid of vertebrates other than fishes
Other invertebrates:	Very Good	*Diadema,* lobster, small crustaceans, and polychaetes abundant; some large sensitive anemone species present
	Good	*Diadema,* lobster, small crustaceans, and polychaetes less abundant than Levels 1–2; large sensitive anemone species absent
	Fair	*Diadema* absent; *Palythoa* overgrowing corals; crustaceans, polychaetes and sensitive anemones conspicuously absent
	Poor	Few or no reef invertebrates; high abundance of sediment dwelling organisms such as mud-dwelling polychaetes and holothurians
Algae:	Very Good	Crustose coralline algae abundant; turf algae present but cropped and grazed by *Diadema* and herbivorous fish; low abundance of fleshy algae
	Good	Crustose coralline algae present but less than Levels 1–2; turf algae present and longer, more fleshy algae present than Levels 1–2

	Fair	Some coralline algae present but no crustose coralline algae; turf is uncropped, covered in sediment; abundant fleshy algae (e.g., *Dictyota*) with high diversity
	Poor	High cover of fleshy algae (*Dictyota)*; complete absence of crustose coralline algae
Organism Condition:	Very Good	Low prevalence of disease and tumors; mostly live tissue on colonies
	Good	Disease and tumor presence slightly above background level; more colonies have irregular tissue loss
	Fair	Higher prevalence of diseased corals, sponges, gorgonians; evidence of high mortality; usually less tissue than dead portions on colonies
	Poor	High incidence of disease and low or no tissue coverage on small colonies of corals, sponges, and gorgonians, if present

Benthic BCG Model

Why benthic organisms?

Reefs in Puerto Rico were historically dominated by the reef-building coral taxa *Orbicella annularis, Orbicella faveolata, Orbicella franksi, Agaricia agaricites, Montastraea cavernosa, Porites astreoides* and *Colpophyllia natans* and *Acropora palmata*. *Acropora palmata* and *Acropora cervicornis* often formed dense, high-relief monospecific thickets; *A. palmata* in shallow exposed forereef habitats and *A. cervicornis* on fore reefs and in shallow, protected back-reefs (Morelock et al. 2001). Corals of the genus *Orbicella* are critical for the biodiversity of fish and invertebrates (Beets and Friedlander 1998; Mumby et al. 2008). *A. palmata* and *A. cervicornis,* listed as a threatened Caribbean species in 2006 under the National Marine Fisheries Service (NMFS), also significantly contribute to reef growth, development, and also provide essential habitat for fish (NOAA 2012).

Together with stony corals, octocorals, sponges, and gorgonians form the three-dimensional reef habitat that supports a multitude of fish, crustaceans, mollusks, and other animals. Undisturbed coral reef habitats possess a wide range of morphologies that provide habitable surface areas for fish and other organisms (Alvarez-Filip et al. 2009; Lirman 2013). Crustose coralline algae are also important because they bind coral skeletons and provide settling sites for coral larvae. Coral reefs have also been shown to protect coastlines from erosion, flooding, and storm damage (UNEP- WCMC 2006; WRI 2009; Principe et al. 2012; Ferrario et al. 2014; Yee et al. 2015).

Some organisms on the reef can kill and overgrow corals and crustose coralline algae, or prevent coral larvae from settling (e.g., macroalgae, cyanobacteria and peyssonnelids). In thriving reefs, these organisms are naturally present at low proportions of the reef community. Impacts to water quality (e.g., increased nitrogen, phosphorous, iron) can enable these faster-growing organisms to out-compete many other benthic species by overgrowth and reduction of larval settlement. This can cause phase shifts to algal-dominated communities that are difficult to re-establish as thriving reefs.

The benthic BCG focuses on the structural and functional importance of benthic organisms including reef-building corals, algae, and other invertebrates, how they interact, and how they indicate overall reef condition. Through the process of model development, all benthic organisms were addressed as potential metrics of biological condition. However, as the model was refined from narrative to numeric characteristics, coral species and metrics became prominent and other benthic organisms were rarely used. We continue to describe all benthic organisms because the narrative expectations were discussed by the experts, regardless of utility in the models.

Narrative Benthic Model

Data used in developing the narrative rules.

The narrative BCG rules were derived using data from the EPA 2010 and 2011 surveys. The reef sites the experts assessed ranged from BCG Level 2 to BCG level 6 (fully degraded). A narrative description of BCG Level 1 characteristics was developed and based on historical narrative descriptions of reefs from the published literature; several included numeric estimates of percent cover of various reef fauna (**Appendix L**, Weil 2020). Quantitative surveys of reef conditions were uncommon and difficult before SCUBA technology was introduced in the 1960s, after widespread human induced changes in reef structure were evident or suspected (**Appendix L**). Many of the historical descriptions were relative to more recent declines in conditions resulting from anthropogenic disturbances.

Data sheets for individual monitoring sites contained taxa lists, attribute-based metrics, coral cover metrics, and metrics of other cover types. An example of the benthic information evaluated by the expert panel for a single site is shown as screenshots of an Excel workbook (**Figures 16 and 17**). Metrics were calculated as in **Appendix G**.

ExerciseID	Samp0037			Assigned Level	Reasoning
Date	11/30/2011				
Method	USEPA				

ATTRIBUTE SUMMARY

BCG Attribute	Number of Taxa	Colony Density (#/m²)	% Cover (2D, live)	% of Taxa	% of Colonies	% of total CSA (2D)
I	0	0.00	0.0	0	0	0
II	1	0.04	0.1	13	2	1
III	1	0.04	0.1	13	2	1
IV	1	0.16	0.2	13	10	3
V	5	1.44	6.8	63	86	95
VI	0	0.00	0.0	0	0	0
x	0	0.00	0.0	0	0	0
Total	*8*	*1.68*	*7.2*			

TAXA LIST

BCG Attribute	Scientific Name	Colony Density (#/m²)	% Mortality	3D Total Surf Area (cm²/m²)	3D Live Surf Area (cm²/m²)	% Cover (2D, live)	3D Av Total Colony Surf Area (cm²/colony)	3D Av Live Colony Surf Area (live cm²/colony)	2D Av Live Colony Surf Area (live cm²/colony)
	TOTALS	*1.68*		*1503.2*	*1153.7*	*7.2*			
IV	*Agaricia humilis*	0.16	0.0	16.5	16.5	0.2	103.1	103.1	137.4
II	*Isophyllia sinuosa*	0.04	0.0	19.2	19.2	0.1	481.1	481.1	176.7
III	*Madracis decactis*	0.04	35.0	37.7	24.5	0.1	942.5	612.6	204.2
V	*Porites astreoides*	0.52	28.2	133.4	95.7	0.7	256.6	184.1	127.6
V	*Pseudodiploria strigosa*	0.16	16.0	227.4	190.9	1.1	1421.1	1193.2	674.2
V	*Siderastrea radians*	0.04	0.0	3.1	3.1	0.0	77.0	77.0	78.5
V	*Siderastrea siderea*	0.64	24.5	1049.8	792.1	5.0	1640.4	1237.7	779.4
V	*Stephanocoenia intersepta*	0.08	27.8	16.1	11.6	0.1	201.3	145.3	94.2

Figure 16. Screenshot of benthic organism data sheet (MS Excel) used in assessing EPA 2010 and 2011 data. This view shows the taxa list, including the assigned BCG attribute, scientific and common names, density, % mortality, and various calculated metrics.

STATION AND SAMPLE CHARACTERISTICS

StationID	PR11-28
Region	Guayanilla/Jobos
Latitude	17.9578
Longitude	-66.5899
Reef Type	Linear Reef
Depth (Coral, ft)	19
Distance (shore, km)	0.78
Distance (shelf, km)	5.28
Distance (disturbance)	22.79
Sediment Threat	0.00
Rugosity Index (EPA)	1.208
Diadema (#/100 m²)	0
Coral Density (col/m²)	1.68
Height sd (cm)	6.24
Coral 2D Live Cover (%)	7.2%
3D live surface area (% of col area)	76.7%
CSA Total (3D, cm²/m²)	1503.2
CSA Total Live (3D, cm²/m²)	1153.7
Sponge Density (#/m²)	3
Gorgonia Density (#/m²)	2.2
Sponge Morph Richness (5m²)	2
Gorgonia Morph Richness (5m²)	2
Fish, Richness (taxa/100m²)	15

Figure 17. Screenshot of Excel worksheet: site and sample characteristics used in assessing EPA 2010 and 2011 data, with sample metrics.

Reef Classification

The selection of habitat classification category for model development is essential for reliable, accurate assessments and ultimately for reliable, robust monitoring and assessment. Classification is critical for establishing the benchmark, or reference, for assessing condition of a site. A robust classification approach enables discrimination between assemblage changes due to natural variability and changes due to anthropogenic disturbance. To establish the foundation for the BCG model, the expert panel selected a habitat classification framework as the basis for rule development and to guide future monitoring. Coral reef environments have distinct horizontal and vertical zones created by differences in depth, wave and current energy, temperature, and light (Zitello et al. 2009). Important physical traits to consider while determining expected species composition of a site include reef zones, geology, sea level change, and sediment exposure (Hubbard 1997; Hubbard et al. 2009; Costa et al. 2009; 2013; Zitello et al. 2009). The Coastal and Marine Ecological Classification Standard (CMECS) developed by the Marine and Coastal Spatial Data Subcommittee Federal Geographic Data Committee (FGDC 2012), states: "All coral reef environments contain distinct horizontal and vertical zones created by differences in depth, morphology, wave and current energy, temperature, and light (Zitello et al. 2009)." Goreau and Land (1974) developed a morphology-based reef classification for Discovery Bay, Jamaica that is common for Caribbean reefs: shallow reef, fore reef, forereef slope, deep fore reef, and the reef wall.

The panel's consensus was to use the NOAA Benthic Habitat Reef Classification Scheme (Costa et al. 2009, 2013); a hierarchical structure that classifies benthic habitat into reef types, geographic zones, and geomorphological structures. Only sites classified as fore reefs were used in this model development, which closely aligned with the data sets. The forereef zone is defined as the area along the seaward edge of the reef crest that slopes into deeper water on the barrier or fringing reef type (Costa et al. 2013). Features associated with a non-emergent reef crest but still having a seaward-facing slope that was significantly greater than the slope of the bank/shelf, were also designated as fore reef. The fore reefs were further divided into two zones; one was dominated by *Orbicella* species, and the other was hard bottom primarily colonized by gorgonians (Williams et al. 2015). The former zone was emphasized in this study.

Coral BCG Attributes

The BCG Attribute categories provide a basis for summing up shared characteristics among taxa and for some experts can facilitate examining the structure and function of sample composition (EPA 2016). The benthic experts had lengthy discussions about the terminology used in the BCG Attribute definitions (**Appendix B**). They agreed that abundance, dominance, frequency, vitality, fidelity, and natural variations or cycles were useful traits for identifying indicator species. The experts felt that the term "ubiquitous" (especially for Attribute IV) means a species is observed on every dive at least once at each site. It is not ubiquitous if the surveyor must search for it. The concept is that the species is widely distributed within a given habitat.

The coral experts assigned BCG Attributes to 48 scleractinian and hydrozoan coral species found in the Western Atlantic based on their known sensitivity and tolerance to human-induced stressors or their origin in the Caribbean region. They identified elevated sea temperature anomalies and land-based pollution (e.g., sediment, nutrients, and contaminants) as the most critical stressors on Caribbean stony corals. Because studies documenting the tolerances of coral species to different anthropogenic stressors are limited, assignments were based on expert knowledge and panel consensus. The rationale for the decisions made on attribute assignments was fully documented. The experts agreed stressors must be independently evaluated, because there is no evidence to suggest a given species would have the same sensitivity to multiple stressors. They assigned an attribute to each species for elevated temperature exposure (as happens before a bleaching episode) and for sediment exposure as a surrogate for land-based pollution (**Appendix M**). For the final attribute assignments to represent a general stressor gradient and to be used in metrics and models, the attributes assigned for sediments were used. The experts did not associate any species with Attribute I, only two species were associated with Attribute II (*Isophyllia rigida* and *Isophyllia sinuosa*), and one species was associated with Attribute VI (non-native taxa). Twenty-three coral species were not associated with attributes because little is known of their sensitivity. Assignments to other species are as follows: Attribute III – 9 species, Attribute IV – 22 species, Attribute V – 13 species.

Narrative Descriptions of BCG Levels

The benthic experts used 46 forereef sites from the 2010 to 2011 Puerto Rico surveys to calibrate the narrative model for the BCG Levels derived from 358 individual expert ratings (an average of 8 experts per sample). The experts developed narrative decision rules for each BCG Level based on perceived patterns of decreasing total percent coral cover, accompanied by higher percentages of tissue loss on individual coral colonies with increasing BCG Level (**Table 7**). As the reef condition decreased with deteriorating environmental conditions, moving down the gradient from BCG Levels 2, 3 or 4 to Levels 5 and 6, reef rugosity decreased, mortality of coral colonies increased, and disease prevalence increased. Algal composition also changed as the BCG Levels changed. In better conditions, crustose coralline algae were more abundant, however with degradation turf and fleshy algae increased. Algal characteristics were determined from videos and photos as no algal surveys were performed. As reefs degraded, the number of rules or descriptors of condition decreased until BCG Level 6 was defined by virtual absence of most taxa found in BCG Levels 1 - 5.

Table 7. Benthic BCG Narrative Rules. Continued on following pages.

BCG Level2 (minimally disturbed)	
Stony corals	• > 45% live cover of coral in fore reef habitat • Minimal recent mortality in large reef-building genera (*Orbicella, Pseudodiploria, Colpophyllia, Acropora, Dendrogyra*) • Normal frequency distribution of colony sizes within each species size range to include large, medium, and small colonies (≥ 4 cm) and presence of recruits (≤ 4 cm) • Species composition and diversity: composed of sensitive, rare species (*Isophyllia, Isophyllastrea, Mycetophyllia, Eusmilia, Scolymia*) present in appropriate habitat type • Very low or just background levels of disease, tissue and skeletal anomalies, and bleaching • *Orbicella* (fore reef), *Acropora* (back reef, reef crest) colonies dominant reef structure within respective zones
Rugosity	• High rugosity resulting from large living coral colonies, producing spatial and topographical complexity
Macroinvertebrates	• *Diadema* abundant • Reef macroinvertebrates (e.g., Lobsters, crabs) common and abundant • Low levels of invertebrate coral predators (*Coralliophila spp, Hermodice spp*)
Algae	• Minimal fleshy, filamentous, and cyanobacterial algae present • Crustose coralline algae present, with some turf algae
Sponges	• Phototrophic sponges dominate • Low frequency of Clionid boring sponges
Water Quality	• High clarity, low particulates
BCG Level 3	
Stony corals	• > 25% live cover of coral in forereef habitat • Higher % of tissue loss with signs of recent mortality especially on large reef-building genera (*Orbicella, Pseudodiploria, Colpophyllia, Acropora, Dendrogyra*) • Frequency distribution of colony sizes within each species size range starting to become skewed to include fewer medium and small colonies (≥ 4 cm) and lower number of recruits than expected (≤ 4 cm) • Species composition and diversity: sensitive, rare species present in appropriate habitat

	• Low to moderate levels of disease and bleaching • *Orbicella* and *Acropora* colonies still dominant (within respective reef geomorphological zones)
Rugosity	• Moderate to high rugosity or reef structure resulting from large living reef-forming and dead coral colonies, producing spatial complexity (or topographical heterogeneity)
Macroinvertebrates	• *Diadema* present • Reef macroinvertebrates (e.g., lobsters, crabs) present
Algae	• Minimal presence of fleshy, filamentous, and cyanobacterial algae cover • Crustose coralline and turf algae present
Sponges	• Phototrophic sponges present • Low cover and abundance of Clionid boring sponges
Water Quality	• Moderate quality and medium water clarity
BCG Level 4	
Stony corals	• > 15% live cover of coral in appropriate habitat • Moderate amount of recent mortality on reef-building genera (*Orbicella, Pseudodiploria, Colpophyllia, Acropora, Dendrogyra*) • Mix of colony sizes: large colonies may be absent, primarily medium and small colonies; low number of recruits • Species composition and diversity: sensitive species may be absent (*Agaricia, Mycetophyllia, Colpophyllia*, etc.), more tolerant spp present (*Montastraea cavernosa, Siderastrea siderea, Porites astreoides)*; at least some reef-building corals present but not primarily dominant (*Orbicella*) • Moderate to high levels of disease and potential bleaching on corals and sea fans/branching gorgonians
Rugosity	• Usually lower rugosity due to old, mostly dead coral structure
Macroinvertebrates	• *Palythoa* may be present, but not dominant
Algae	• Moderate to high amount of fleshy, filamentous, and cyanobacterial algae cover
Sponges	• Moderate cover and abundance of Clionid boring sponges
Water Quality	• Quality could be poor with low clarity and high particulates

BCG Level 5	
Stony corals	• > 1% live cover of coral in appropriate habitat but less than 15% • High mortality on most colonies, present primarily on small colonies
Rugosity	• Low rugosity composed of mostly dead and eroded coral structure
Algae	• Coral cover replaced by fleshy, filamentous, and cyanobacterial algae
Macroinvertebrates	• *Palythoa* dominant
Sponges	• Highest presence of Clionid boring sponges • Non-phototrophic sponges dominant
Water Quality	• Probably persistently poor quality, low water clarity, high turbidity

Numeric Model – Calibration and Validation

***Developing the numeric rules*.**

In developing the numeric rules, bioassessment data from NOAA NCRMP 2013 – 2015 surveys in Puerto Rico and the USVI were used. While the NCRMP field sampling protocols were similar to those described above for the EPA Puerto Rico data, there are some important differences. For example, EPA did not use the Line-Point Intercept method. Also, NOAA did not include morphology and sizes of sponges and gorgonians as was done in the EPA DEMO surveys, and used a microheterogeneity approach (MRV) for reef rugosity while sampling down to 100-foot depths. The expert opinion was that the LPI data including the benthic coverage was more important than the sponge and gorgonian 3D measurements, and because the NOAA method was intended for continued application in monitoring programs, calibration of the numeric model was based on the NOAA data.

The deepest sites in the data set were approximately 100 feet deep, which is the maximum practical depth for scuba diver-based underwater monitoring (Brylske 2006). Within this depth range, the experts suggested that differences in reef structure occurred at approximately 40 feet deep, as a result of gradual differences in light penetration and wave action. However, when experts attempted to develop depth-dependent rules, biological differences among the depth strata were not distinguishable. Therefore, the sample sites used in model development were from depths from the entire 100-foot depth range. Differences in natural expectations and assessment results relative to depth were assessed during and after the BCG rating and prediction processes. Data sheets for individual sites included site and sample information (including site depth) with taxa lists, attribute-based metrics, coral cover metrics, and metrics of other cover types (**Figures 18 and 19**).

ExerciseID	Samp9654	Best Tier	NA	Rating	Rationale
Collection Date	7/24/15	Median Tier	NA		
Collection Method	NCRMP	Worst Tier	NA		

CORAL ATTRIBUTE SUMMARY - DEMO

BCG Attribute	Number of Taxa	Colonies/m²	% Taxa	% Cover (LPI)	LCSA 2D (cm²/m²)	CSA 3D (cm²/m²)	LCSA 3D (cm²/m²)
I	0	0	0%	0%	0	0	0
II	0	0	0%	0%	0	0	0
III	3	0.8	25%	3%	724	817	684
IV	4	3.1	33%	30%	6452	10539	7303
V	5	1.1	42%	4%	255	637	583
VI	0	0	0%	0%	0	0	0
NA	0	0	0%	1%	0	0	0
Total	*12*	*5*	*100%*	*38%*	*7431*	*11993*	*8570*

Live 2D_cm²	Live % cover	Total 2D_cm²	Total % cover
6404.8	64.0	8134.10011	81.3

Based on median max diameter & mean mortality per species

Note:
To convert LCSA_2D cm²/m² to % 2D cover:
divide LCSA_2D by 100

CORAL TAXA LIST - DEMO

"-1" in demographic value indicates juvenile < 4cm

BCG Attribute	Scientific Name	Demo Colonies	Demo Colonies/m²	Mean Mortality Old (%)	Mean Mortality New (%)	Max Diameter (cm) Min	Max Diameter (cm) Median	Max Diameter (cm) Max	Height Max (cm)	LCSA_2D cm²/m²	CSA_3D cm²/m²	LCSA_3D cm²/m²	# Bleached (part/total)	# Diseased (colonies)
4	*Agaricia agaricites*	4	0.4	0	0	10	20	30	3	115	43	43	2P/0T	0
3	*Agaricia lamarcki*	5	0.5	7	0	11	37.8	65	40	667	726	602	0P/0T	0
3	*Colpophyllia natans*	1	0.1	0	0	23	23	23	2	47	34	34	0P/0T	0
3	*Madracis decactis*	2	0.2	10	0	4	9.5	15	7	9	58	48	0P/0T	0
4	*Meandrina meandrites*	1	0.1	25	0	50	50	50	8	170	209	157	0P/0T	0
5	*Montastraea cavernosa*	3	0.3	15	0	11	18	27	19	91	359	324	0P/0T	0
4	*Orbicella faveolata*	6	0.6	15	0	29	53.6667	80	10	1374	1400	1089	0P/0T	0
4	*Orbicella franksi*	20	2	25.25	0	22	59.8	110	40	4792	8887	6015	2P/0T	0
5	*Porites astreoides*	4	0.4	5	0	11	18.5	26	10	120	208	191	0P/0T	0
5	*Siderastrea radians*	1	0.1	0	0	5	5	5	3	2	6	6	0P/0T	0
5	*Siderastrea siderea*	2	0.2	2.5	0	11	13.5	16	7	34	56	55	1P/1T	0
5	*Stephanocoenia intersepta*	1	0.1	0	0	9	9	9	2	7	8	8	0P/0T	0
	TOTAL	**50**	**5**											

Coral Taxa List - LPI

BCG Attribute	Scientific Name	% Cover
IV	*Agaricia agaricites*	2
III	*Agaricia lamarcki*	1
III	*Colpophyllia natans*	2
IV	*Meandrina meandrites*	1
NA	*Millepora spp*	1
V	*Montastraea cavernosa*	1
IV	*Orbicella faveolata*	10
IV	*Orbicella franksi*	17
V	*Siderastrea radians*	1
V	*Stephanocoenia intersepta*	2
	TOTAL	**38**

Reviewed previously and during the webinar

Webinar notes

EW: this is a very deep site, for that depth those metrics are pretty good. The model gives it a 3 but it could easily be a 2 for the depth of habitat for

AS: agrees with EW

BW: agrees with EW, given the depth, it bumps it up to a higher level

TS: given the depth, most of the reefs at this depth are like this so idk if this is atypical

i. BW: depends on how impacted the area is

AS: just based on the data, DEMO % is really high (LPI is not), but going back to historical, would give it a 2

HR: thinks this is a 3 based on data and not photo

i. Data he uses is LPI %cover and macroalgae

BF: concerned about changing the model, if we start adding concerns over depth, then its not consistent, will start to have a separate model and r

Figure 18. Screenshot of the benthic organism data sheet (MS Excel) used in assessing NOAA NCRMP data: This view shows the taxa list, including the assigned BCG attribute, scientific and common names, density, % mortality, and various calculated metrics.

STATION AND SAMPLE CHARACTERISTICS		LPI (% Cover)	
Station ID	M78	SEAGRASS	0
Latitude	18.295581	BARE SUBSTRATE	5
Longitude	-64.750031	SPONGES	2
Distance (shore, km)		*Porifera spp*	2
Distance (shelf, km)		*Cliona spp*	0
NOAA Habitat Type (Kendall)	MSR_OPEN_PTRF_DEEP	SCLERACTINIAN CORALS	38
Habitat Type by Diver		OCTOCORALS	4
Depth (min-max) (feet)	86-95	Encrusting Gorgonians	3
Depth Strata	DEEP	Branched Gorgonians	1
Microheterogeneity	0.750	ZOOANTHIDS	0
% Substrate Types	96% Hard / 4% Soft	*Palythoa* spp	0
LPI (% Cover)		OTHER SPP	0
ALGAL GROUPS	51	Mobile Invertebrates	
Cyanobacteria/Diatoms	3	*Diadema antillarum*	0
Cyanobacteria spp	3	*Aliger gigas*	0
Macro Fleshy	36	*Panulirus argus*	8
Dictyota spp	7	ESA Taxa (Presence/Absence)	
Lobophora spp	29	*Acropora cervicornis*	0
Other Fleshy spp	0	*Acropora palmata*	0
Macro Calcareous	5	*Agaricia lamarcki*	0
Halimeda spp	0	*Dendrogyra cylindrus*	0
Peysonnellia	5	*Dichocoenia stokesii*	0
Other Calcareous spp	0	*Mycetophyllia ferox*	0
Crustose Coralline	3	*Orbicella annularis*	0
Ramicrusta	3	*Orbicella faveolata*	1
Turf Algae	4	*Orbicella franksi*	1
Turf Algae Free of Sediment	0	Fish	
Turf Algae with Sediment	4	Fish, Richness	54
		Fish, Diversity	1.482

Figure 19. Example data from Excel worksheet: Station and sample characteristics used in assessing NOAA NCRMP data. This view shows information about the station and metrics calculated at the site scale.

In webinars and the final workshop, experts reviewed 72 NCRMP sites, resulting in BCG Level assignments for 57 sites. Initially 66 sites were considered but those that lacked both LPI and DEMO data, or that were not valid forereef habitat (gorgonian plains or bedrock), were not used in model development. The 57 sites were from Puerto Rico and the USVI and included deep and shallow habitats (**Table 8**).

Table 8. Numbers of sites used for development of the benthic BCG model, showing location, depth, and sampling method.

BCG Level		3	4	5
Island	St. Thomas/ St. John	16	10	2
	St. Croix	3	11	3
	Puerto Rico	0	13	8
Depth	Shallow (<40')	2	12	11
	Deep (>40')	17	22	2
Method	LPI and DEMO	17	28	12
	LPI only	2	6	1

From these sites, the metrics were tested for discrimination between BCG Levels. Each metric was plotted to show its values distributed among sites within BCG Levels rated by its experts. The experts used the plots to confirm the narrative rules and to the analyst tested quantitative rule thresholds (**Figures 20-22**). The analyst formulated model drafts by applying the rule thresholds in combination at each Level. The experts reviewed and revised the drafts iteratively until the predictive BCG model was finalized (**Table 9**).

When separation between Levels showed that the better Level had consistently better metric values, the rule was developed so that there were few errors in identifying the better Level. In these cases (like the rules for Level 2), all the rules were required and the rules were combined with “AND” logic. In other cases, when the panel was clearly considering an either/or situation, alternative rules were applied using “OR” logic. Panelists were not always aware they did this – it became apparent when the draft numeric model yielded poorer BCG levels than the panel, i.e., the numeric model was too stringent. Upon discussion, the panel generally agreed to an “OR” logic for combining the given rules (like the rules for Level 4).

Combination rules at Level 2 of the benthic BCG model are that all the rules are required, meaning the "AND" logic is applied (Rule 1 and 2 and 3 and 4). The experts expected that all the rule conditions must be attained for a site to be exhibit Level 2 conditions. This is derived numerically by calculating the membership value for each rule then finding the minimum of those four values. The minimum rule membership value is the site membership for Level 2.

At Level 3, five rules were included in the model. The experts expressed that the first four rules were required. However, they also expressed that if the percent live *Orbicella* cover (DEMO) was high, it was a more meaningful indication of Level 3 conditions than the other rules. In this case, the minimum membership value of the four rules is compared to the membership value for the fifth rule and the maximum of that comparison is the site membership in Level 3.

At Level 4, seven rules were used to describe biological conditions. However, because of diverse Level 4 conditions, all of which were recognizable by the experts, all the rules were not expected to indicate Level 4 at the same site. All the metrics used in the rules showed considerable overlap with metric values of Level 5 sites. Therefore, if only three rules indicated Level 4, then the site satisfied requirements for Level 4. Hardly any of the Level 5 sites could pass three of the seven rules. To calculate the site membership in Level 4, The best three membership rules were compared and the minimum of these was used as the site membership in Level 4.

At Level 5, three rules were defined, two of which needed to be satisfied. In other words, one rule could be discounted; the one with the lowest membership value. Because the rules are applied in order from Level 2 to Level 5, any site not meeting any of the Level 5 rules is automatically predicted to be Level 6.

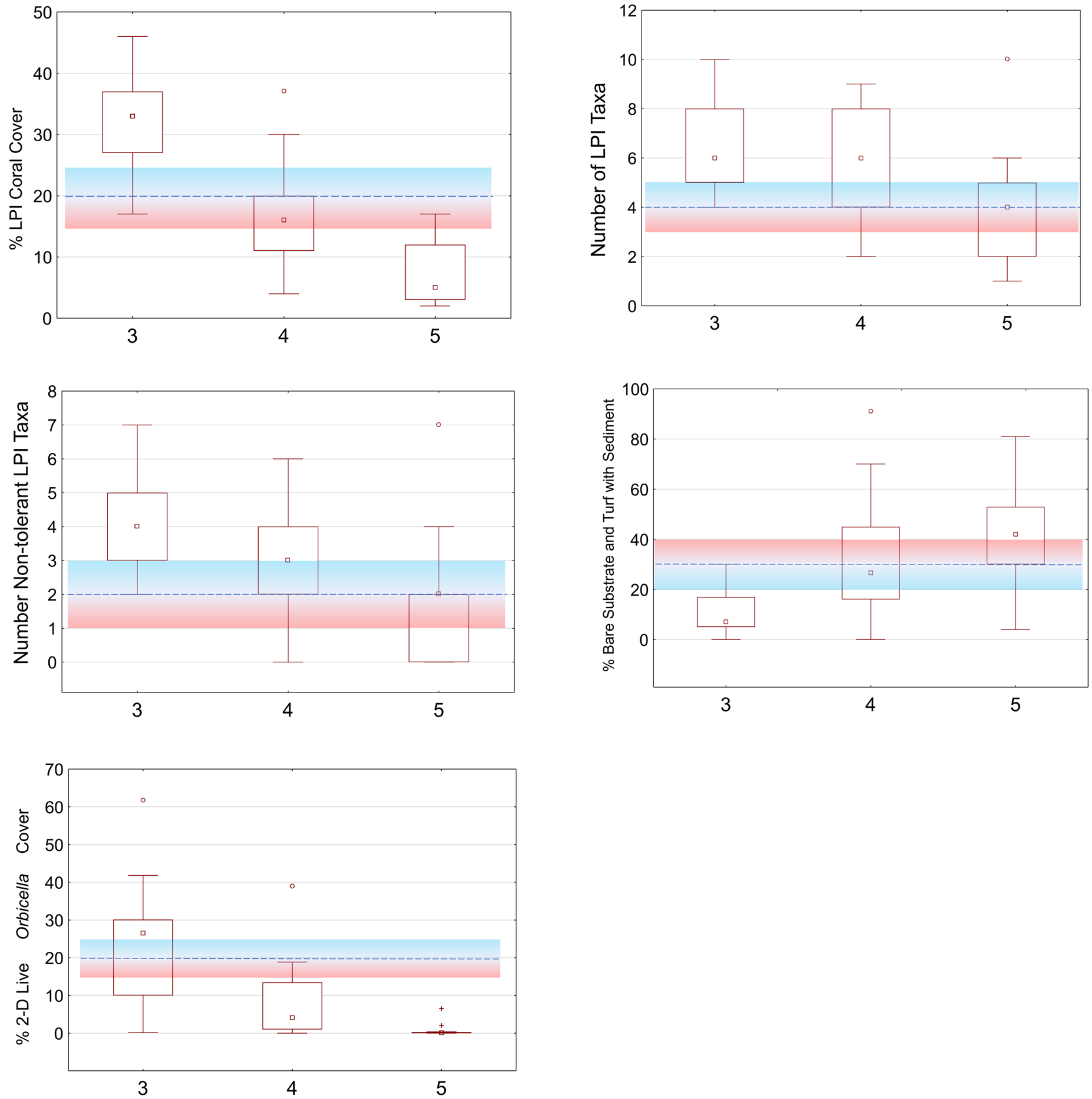


Figure 20. Distribution of metrics used in model rules for discriminating Benthic BCG Levels 3 and 4, showing the rule thresholds (dashed line) and ranges (color-shaded region). Membership values are calculated as 1.0 if the metric value is better than the blue range, 0.0 if worse than the red region, and interpolated between 0.0 and 1.0 if within the shaded region. Distributions include the median (central square), interquartile range (rectangular box), non-outlier ranges (whiskers), and outliers (circular marks).

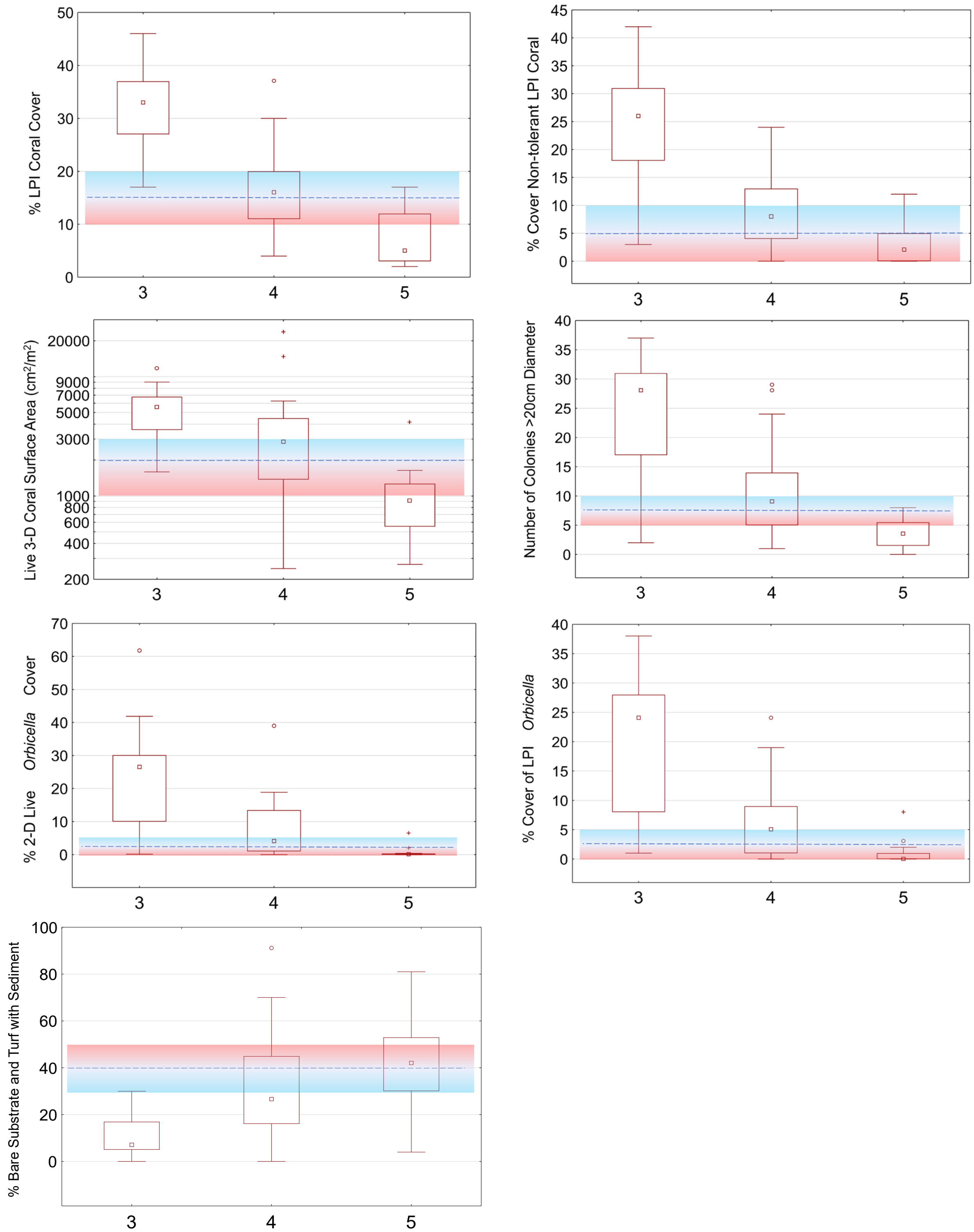


Figure 21. Distribution of metrics used in model rules for discriminating Benthic BCG Levels 4 and 5, showing the rule thresholds (dashed line) and ranges (color-shaded region). Membership values are calculated as 1.0 if the metric value is better than the blue range, 0.0 if worse than the red region, and interpolated between 0.0 and 1.0 if within the shaded region. Distributions include the median (central square), interquartile range (rectangular box), non-outlier ranges (whiskers), outliers (circular marks), and extremes (stars).

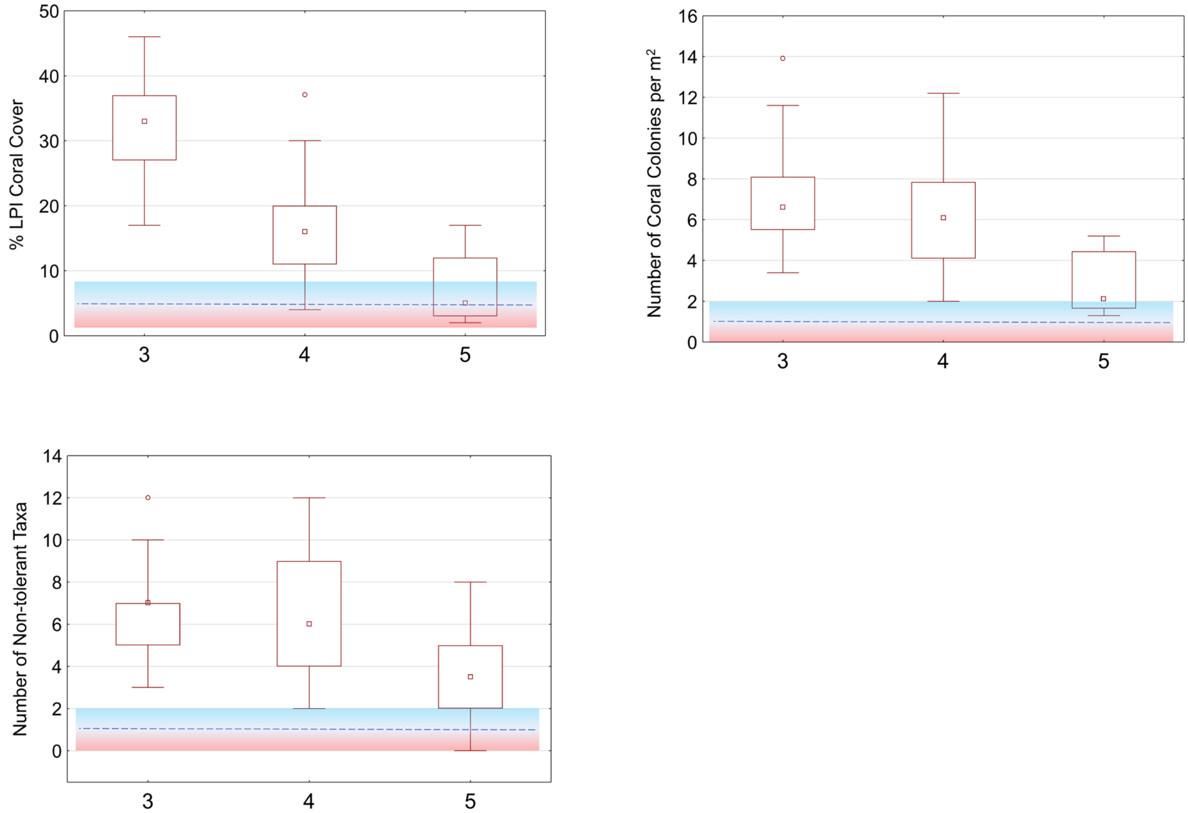


Figure 22. Distribution of metrics used in model rules for discriminating Benthic BCG Levels 5 and 6, showing the rule thresholds (dashed line) and ranges (color-shaded region). Membership values are calculated as 1.0 if the metric value is better than the blue range, 0.0 if worse than the red region, and interpolated between 0.0 and 1.0 if within the shaded region. Distributions include the median (central square), interquartile range (rectangular box), non-outlier ranges (whiskers), outliers (circular marks), and extremes (stars).

Table 9. BCG predictive model rules for the coral reef benthic assemblage (first generation), showing the Level definition (details in Appendix C), narrative rules, quantitative rules, and rule combinations. In application, sample metrics were tested first at Level 2. Level 3 rules were applied next, but only if Level 2 rules were not met with 100% membership. The rules were likewise applied at Levels 4 and 5 until site membership was established. If rules were not met at Level 5, then the site was determined to be Level 6 by default. In the quantitative rules, the numeric range is shown so that partial membership can be determined for each rule at each Level. Continued on following pages.

BCG Level 1	**Definition:** Natural or native condition—native structural, functional, and taxonomic integrity is preserved; ecosystem function is preserved within the range of natural variability **Narrative**: Level 1 and 2 narratives were combined for the coral reef exercise; no quantitative rules were developed for Level 1	
BCG Level 2	**Definition:** Minimal changes in structure of the biotic community and minimal changes in ecosystem function—virtually all native taxa are maintained with some changes in biomass and/or abundance; ecosystem functions are fully maintained within the range of natural variability **Narrative**: Coral species are highly diverse, including rare species; large old colonies of reef-building species (e.g., *Orbicella*) with high live tissue cover; balanced population structure (old and middle-aged colonies, recruits); Acroporids present	
BCG Metrics	*Narrative Rules*	*Quantitative Rules*
Percent Coral Cover (LPI)	Coral cover high	>40% (35 – 45) [a]
Percent live coral cover (DEMO)	Coral cover high	>30% (20 – 40)
Percent coral mortality (DEMO)	Low percentage of tissue loss (2-D and 3-D cover)	<10% (5-15) [b]
Percent live cover of large, reef-building coral species (DEMO)	Substantial coverage of reef-building taxa	>30% (25 – 35) [c]
Level 2 Combination: Minimum of 4 rules [d]		

BCG Level 3	**Definition:** Evident changes in structure of the biotic community and minimal changes in ecosystem function—Some changes in structure due to loss of some rare native taxa; shifts in relative abundance of taxa but intermediate sensitive taxa are common and abundant; ecosystem functions are fully maintained through redundant attributes of the system	
	Narrative: Moderate coral diversity; large old colonies (*Orbicella*) with some tissue loss; varied population structure (usually old colonies, few middle-aged, and some recruitment); *Acropora* thickets may be present; rare species absent	
BCG Metrics	*Narrative Rules*	*Quantitative Rules*
Percent Coral Cover (LPI)	Moderate coral cover	> 20% (15-25)
Total Coral Richness (LPI)	Moderate coral richness	> 4 species (3-5)
Non-tolerant Coral Richness (LPI)	Non-tolerant BCG Attribute I, II, III, IV taxa are present	> 2 species (1-3) [e]
Bare Substrate and Turf with Sediment Cover (LPI)	Minimal presence of unproductive and sedimented cover	< 30% (20-40)
Percent live *Orbicella* cover (DEMO)	*Orbicella* colonies are important	> 20% (15-25)
Level 3 Combination: Minimum of first 4 rules or the *Orbicella* rule [f]		
BCG Level 4	**Definition:** Moderate changes in structure of the biotic community and minimal changes in ecosystem function—moderate changes in structure due to replacement of some intermediate sensitive taxa by more tolerant taxa, but reproducing populations of some sensitive taxa are maintained; overall balanced distribution of all expected major groups; ecosystem functions largely maintained through redundant attributes	
	Narrative: Reduced coral diversity compared to Level 3; emergence of tolerant species; few or no large old colonies (*Orbicella*), or mostly dead; *Acropora* thickets gone	
BCG Metrics	*Narrative Rules*	*Quantitative Rules*
Percent Coral Cover (LPI)	Low to moderate total coral cover	>15% (10-20)

Non-tolerant Coral Cover (LPI)	Low to moderate non-tolerant BCG Attribute I, II, III, IV cover	> 5% (0-10) [e]
Live Coral Cover (DEMO)	Low to moderate total coral cover (based on surface area 3-D)	> 2000 cm^2/m^2 (1000-3000)
Percent live *Orbicella* cover (DEMO)	*Orbicella* present, though sparse	> 2.5% (0-5)
Percent *Orbicella* cover (LPI)	*Orbicella* present, though sparse	> 2.5% (0-5)
Density of medium or large colonies (DEMO)	Medium size colonies (max D > 20cm) present in the transect	> 7.5 colonies (5-10)
Bare Substrate and Turf with Sediment Cover (LPI)	Moderate presence of unproductive and sedimented cover	< 40% (30-50) [g]
Level 4 Combination: Minimum of the three highest membership values [h]		
BCG Level 5	**Definition:** Major changes in structure of the biotic community and moderate changes in ecosystem function—Sensitive taxa are markedly diminished; conspicuously unbalanced distribution of major groups from that expected; organism condition shows signs of physiological stress; system function shows reduced complexity and redundancy; increased build-up or export of unused materials	
	Narrative: Severely reduced coral diversity, minimal presence of colonies, tolerant species dominant	
BCG Metrics	*Narrative Rules*	*Quantitative Rules*
Percent Coral Cover (LPI)	At least some living coral	> 5% (2-8) [i]
Density of Colonies (DEMO)	At least some living coral	> 1 colony/m^2 (0-2) [j]
Non-tolerant Taxa Abundance	Attribute I, II, III, or IV taxa are present	> 1 species (0-2) [k]
Level 5 Combination: Minimum of the two highest membership values [l]		

BCG Level 6	**Definition:** Severe changes in structure of the biotic community and major loss of ecosystem function. Extreme changes in structure; wholesale changes in taxonomic composition; extreme alterations from normal densities and distributions; organism condition is often poor; ecosystem functions are severely altered.
	Narrative: Absence of colonies; those present are small; only tolerant species; little or no tissue
	Rules: No rules were established for Level 6. By default, failure of Level 5 rules results in a Level 6 model prediction.

Table 9 notes

a. Though the rules for Level 2 were conceptual, the expert panel suggested that total coral cover should be limited to functional/sensitive taxa. The specific rule might address BCG Attribute assignment; specific sensitivities to bleaching, turbidity, and disease; large reef-building coral; or observed large colony size. This comment prompted further refinements and descriptions of coral traits and attributes (see Weil 2019).

b. Although this rule is still conceptual, the expert panel questioned whether they had adequately described expectations for coral mortality in Level 2. It was suggested that perhaps the expectation of <5-15% mortality was too strict. Also, the specification of old or new mortality might be used to further refine the rule.

c. Large Reef-Building Corals (LRBC) include the genera *Orbicella, Acropora, Diploria, Pseudodiploria, Colpophyllia, and Dendrogyra, and species of Montastraea cavernosa,* and *Siderastrea siderea. Orbicella* and *Acropora* are the major reef building coral genera in the Caribbean.

d. At the workshop, the experts expressed that the size structure of the coral assemblage might be used to recognize functional Level 2 conditions. The specific size structure metrics (species, size classes, and numeric thresholds) were not detailed during the meeting and no new conceptual rule was developed. Rather, this expectation might be explored in continued research efforts on size expectations per species, recruitment, and size diversity.

e. Attribute I taxa were included because, though they are not specifically non-tolerant, they are in some way specialists, endemic, or long-living.

f. Live 2D cover of *Orbicella* does not need to be high for a reef to be Level 3 (if *Orbicella* cover is <20%, the minimum of the other rules is the predicted membership of Level 4). However, if *Orbicella* cover is >20%, then the *Orbicella* rule alone can override the minimum of the other four rules.

g. The expert panel expressed that a rule regarding algae should be applied in Level 4. The rule on bare substrate and turf algae with sediment was added compared to the previous model draft.

h. The expert panel suggested that three rules should be met instead of only two that were required in the previous model draft. This rule on its own would result in additional model errors, but when also adding the bare substrate and turf with sediment rule, no additional model errors result. The Level 4 rule thresholds were established to identify possible Level 4 conditions, rather than to screen out Level 5 conditions, so only a few indications are required.

i. Experts suggested raising the % LPI cover threshold to 5% instead of the previous threshold of 2%. Raising the LPI % cover threshold resulted in 5 errors at Level 5 (predicting Level 6 conditions for this rule).

j. Experts considered that maybe the threshold should be raised. However, no quantitative threshold was proposed, and additional errors may be introduced when raising the threshold, so no change was made.
k. Experts suggested adding a rule about sensitive taxa richness. This rule was added.
l. When the Number of Non-tolerant Tax rule is added and the best 2 of 3 rules are evaluated, there are 2 more errors in comparison to the original rule set, which required evaluation of two out of two rules.

Of the 57 evaluated sites that had both LPI and Demo survey data, the model (first generation) predicted the same BCG Level as assigned by the experts for 48 sites (**Table 10**). The model accuracy is therefore 84% (90% confidence interval: 74 – 92%). No prediction was more than one Level different than the assignment. There were 9 predictions counted as correct that were tied between Levels either in expert assignment or model prediction. For 4 sites, the prediction was counted as an error although the difference from the assignment was very similar. For example, an assigned Level 3- is very similar to a predicted Level 4+, but because they are in different Levels, the prediction was counted as an error.

Table 10. Comparison of expert assignment of BCG Levels for benthic calibration of reef sites compared to BCG Levels predicted by the model, indicating where there was agreement (shaded cells) and disagreement (unshaded cells).

			BCG Model Predictions – Benthic Calibration							
	Rating	Total # Rated	2	3	3-4 tie	4	4-5 tie	5	5-6 tie	6
Expert BCG Assignment	2	0	0	0	0	0	0	0	0	0
	3	17	0	16	0	1	0	0	0	0
	4	25	0	1	4	16	1	3	0	0
	4-5	3	0	0	0	0	0	3	0	0
	5	12	0	0	0	2	0	7	1	2
	6	0	0	0	0	0	0	0	0	0

The expert rating precision was illustrated by comparing the individual experts' ratings to the median rated BCG Level for each site (**Figure 23**). There were 392 individual ratings of valid reef sites. Of those, 68% were within a third of a BCG Level: the difference between a whole BCG Level and a "+", and "-". Nearly all individual ratings (96%) were within 1 Level of the group median. Only one rating was 2 Levels different than the group median (**Figure 23**).

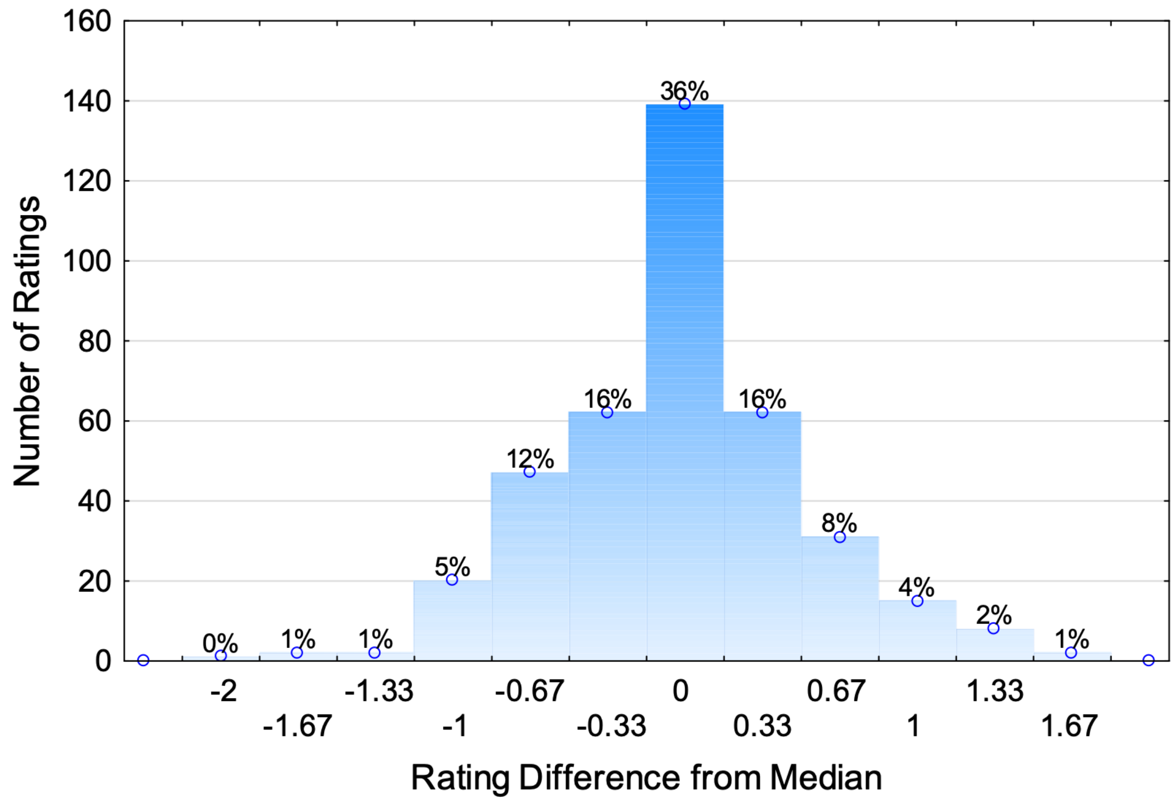


Figure 23. Individual rating precision for calibration sites, measured as the difference between the median BCG Level for a site and the expert's individual rating. Increments are 1/3 to represent whole, "+", and "-" ratings.

Benthic Model Validation

To validate the benthic model with an independent set of forereef sites, 18 valid reef sites were reviewed by nine experts. All but two of the 18 ratings (median per site) matched the model prediction (**Table 11)**, resulting in 89% agreement (90% confidence interval: 69 - 98%). This compares with an 84% agreement rate for the calibration sites and indicates successful validation of the model. Ties in either the expert ratings or the model predictions were deemed correct for adjacent Levels. As seen in the calibration data, the individual ratings were precisely centered around the median rating for each site (**Figure 24**).

Of the two sites where the expert median rating did not match the model prediction, one was a straight disagreement where the experts perceived conditions that were Level 5, and the model predicted a Level 4 condition. The other disagreement between ratings and the prediction was for a site that was rated as a Level 4 but was predicted as a Level 3 because there was more than 25% coverage of live *Orbicella* colonies. Though other rules at Level 3 failed, this rule was applied using "or" logic that over-ruled the others. Despite these disagreements, the experts considered the model to be adequately validated.

Table 11. Comparison of expert ratings of BCG Levels for benthic validation of reef sites compared to BCG Levels predicted by the model, showing where there was agreement (shaded cells) and disagreement (unshaded cells).

			BCG Model Predictions - Benthic Validation							
	Rating	Total # Rated	2	3	3-4 tie	4	4-5 tie	5	5-6 tie	6
Expert BCG Assignment	2	0	0	0	0	0	0	0	0	0
	3	1	0	0	1	0	0	0	0	0
	3-4 tie	1	0	1	0	0	0	0	0	0
	4	7	0	1	0	6	0	0	0	0
	4-5 tie	0	0	0	0	0	0	0	0	0
	5	5	0	0	0	1	0	4	0	0
	6	4	0	0	0	0	0	0	0	4

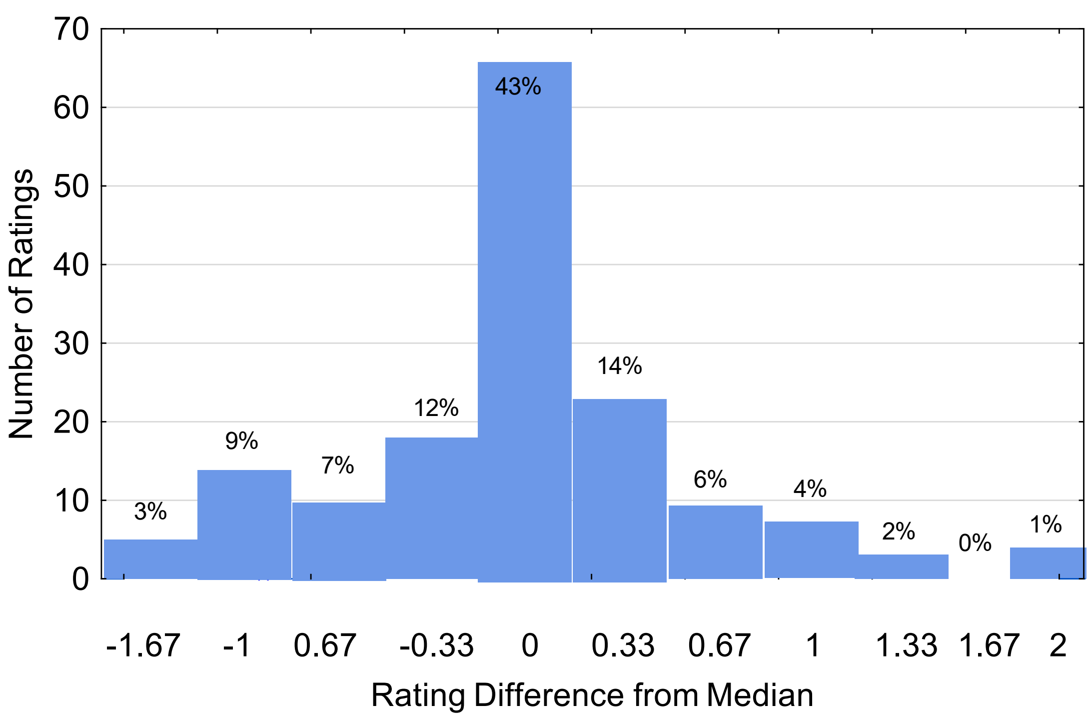


Figure 24. Individual rating precision for validation sites, measured as the difference between the median BCG Level for a site and the expert's individual rating. Increments are 1/3 to represent whole, "+", and "-" ratings.

Benthic Model Discussion

The experts determined that the first generation benthic BCG model can be used to quantitively interpret Caribbean reef conditions ranging from BCG Level 3 to BCG Level 6. The model was based on expert derived numeric decisions rules. There were no Level 2 conditions observed in the NCRMP calibration data used to develop the numeric rules. However, the experts proposed conceptual Level 2 narrative rules based on a limited set of Level 2 EPA sites that the experts observed while developing the narrative model and drawing upon their decades of field experience and knowledge of historical descriptions. The conceptual rules for BCG Level 2 can be used to identify sites that may be of higher quality than the BCG Level 3 rules. A practitioner can make note of a site where the taxa appeared to match a narrative BCG Level 2 condition, and they may consider whether those taxa might be candidate species for protection or conservation based on a follow up assessment.

Level 3 quantitative rules include four LPI metrics and one DEMO metric. The rules in Level 3 are applied as an “either/or” rule. Either all four LPI metrics or the single DEMO metric can be used to assign a site to BCG Level 3. The DEMO rule is defined as high *Orbicella* cover, which was considered by the experts to be a dependable metric of relatively undisturbed reef conditions. At Level 3, the expected characteristics are ample coral cover of various species, most of which are sensitive or moderately tolerant to sediment stress, and non-coral cover that is productive (low benthic coverage of bare substrate or sedimented algal turf).

To be assigned to Level 4, only three of the seven rules must pass for a site, because each metric at Level 4 was more variable, and there were different combinations of metrics that indicated a reef matched the description of BCG Level 4. The experts saw signs of fair conditions in the midst of some poor indications. Moderate LPI cover and *Orbicella* cover were expected at Level 4, but not at values as high as expected at Level 3.

For sites to be assigned to Level 5 rather than 6, there must be at least some live coral cover, and some coral cover comprised of moderately tolerant coral species. If a site did not meet BCG level 5 rules, then it was assigned to BCG Level 6.

This numeric benthic BCG model was accurate in predicting the experts’ median ratings for 84% of the calibration data and 89% of the validation data. The model replicated the expert consensus within one BCG Level for 100% of sites. This degree of accuracy was acceptable to the experts, who considered a one Level difference to be minimal and infrequent. A table listing the metrics used in the BCG Benthic Model rules and ecological/biological importance of each metric is provided in **Appendix N**.

BCG Attribute VII: Organism Condition for Hard Corals

The coral experts discussed hard coral health and biological condition as possible metrics that might be used in model rules. Weil 2020 (**Appendix R**) and Rogers et al. 2020 (**Appendix T**) contend that the species composition of coral reef ecosystems is of less importance than the condition of the colonies and their responses documented by long-term monitoring (with the exception of *Acropora* species (spp.) and *Orbicella* spp.). The condition and health of framework-building corals are important because they are colonial, modular organisms that create the architecture of the reef and can persist for decades in spite of partial mortality to individual colonies. Alternatively, the metrics used in freshwater systems are often species absence or presence and abundance of solitary organisms that live as independent units.

The presence and condition of *Acropora* spp. and *Orbicella* spp. are important to evaluate the overall condition and status of a reef area. Both are the most important and prolific genera for building the architecture of coral reef structures in the Caribbean and Western Atlantic. The presence of "standing dead" *A. palmata* structure provides profound insights into the ecological history of a reef site. *A. palmata* is typically confined to depths <10m. *Orbicella* spp. compose structure in deeper reefs and under environmental conditions not conducive for Acroporid growth and survival. Although the number of coral species (diversity, richness) is informative, it is not as crucial as defining coral condition (Rogers et al. 2020).

Rogers et al. (2020) recommended that an indicator for coral health or condition be developed and tested as a potential metric that could be included at all Levels of the numeric BCG model. The specific recommendation for reef corals was disease prevalence for all tissue loss diseases affecting the coral assemblage at each Level. The tentative guidelines proposed for consideration and further discussion are: BCG Level 1 (0–1 percent); BCG Level 2 (> 1–5 percent); BCG Level 3 (>5–10 percent); BCG Level 4 (>10–20 percent); BCG Level 5 (>20–30 percent); and BCG Level 6 (>30 percent).

Specific measures for health indicators recommended by experts, and the Weil (2020) and Rogers et al. (2020) reports included: incidence and prevalence of specific coral diseases and bleaching, recording which species are affected, percent coral mortality that distinguishes between recent and old colony mortality, vitality of colonies (percent of the colony that is tissue growing over skeleton), and percent and status of diseased and healthy tissue. This process could begin by examining several bioassessment protocols that estimate coral condition used in the USVI Territorial Coral Reef Monitoring Program (TCRMP) (Smith et al. 2008, 2013) and the Atlantic and Gulf Rapid Reef Assessment (AGRRA) (Calnan 2008). These metrics could highlight vulnerable reefs that might be declining and be incorporated into the Benthic Screening Assessment Tool (BSAT).

Ecological Traits for Hard Corals

Weil (2020, **Appendix R**) reviewed the life history, biological, ecological, and geographical characteristics of scleractinian and hydrocoral species recognized in the wider Caribbean that could inform additional traits to consider in future generations of the benthic BCG numeric model. He documented hard coral traits such as current taxonomic status, reproduction, growth, mean colony size, common colony morphology, and both local and geographic distribution. The review described extensive information about coral disease in the Western Atlantic, including the species affected and their susceptibility to both disease and bleaching. Additionally, all hard corals were evaluated to document individual species sensitivity and tolerance to the most prominent anthropogenic threats as determined by the expert panel (sedimentation and elevated sea temperature). The criteria used to define the species response included population survivorship, fitness, and potential resilience.

Benthic Screening Assessment Tool (BSAT)

The metrics used in the numeric BCG model require both LPI and DEMO methods and consume considerable resources and logistics to implement. These resources might not be available for routine monitoring in Puerto Rico and the USVI by the territorial jurisdictions or resource managers. For greater accessibility and less resource intensive bioassessments, abbreviated protocols are recommended to achieve a screening-level assessment of biological conditions. The abbreviated protocols could provide a coarser level evaluation to identify degraded or high-quality reefs. Identifying critical sites could allow a triaging approach to focus efforts and resources on those reefs in critical need of attention due to severe alteration or to further protect those reefs in high quality condition.

The LPI protocol is generally suitable for a screening-level assessment. Nadon and Stirling (2006) found the LPI was a cost-effective, highly accurate, and precise method for measuring benthic cover. They recommended sampling 100 points on a 20m transect using 5-10 randomly positioned replicates within a homogenous area. The LPI methods are simple and quick enough to be used by the territorial monitoring agencies stretched for resources, because they require inexpensive equipment, a single surveyor (with a dive buddy who can take the photographs), and are relatively fast to complete underwater. The benthic screening assessment tool (BSAT) would include elements of the calibrated BCG Benthic Model related to the LPI measurements as well as additional non-LPI elements that could be easily observed and quickly recorded. The BSAT was developed with the sampling limitations in mind.

Four LPI measures were scored in the BCG Benthic Model. Quantitative rule thresholds were derived from existing rules, expert panel remarks, and iterative model testing. The BSAT applies these LPI rules from the BCG Benthic Model. These include % LPI coral cover, % bare substrate and turf algal cover with sediment (2 categories combined), and number of non-tolerant (BCG

Attributes IV and V) coral species. Percentage of *Orbicella* and *Acropora* cover were included for assessment of the good and fair conditions.

Additional measures that were often discussed by the experts as critical indicators of condition included % mortality and number of diseased colonies. These were only measured in the DEMO methods and would need to be estimated if used for any screening-level assessments. Excessive mortality, especially recent mortality, could be estimated by divers while surveying with the LPI methods. An estimation protocol might include diver notations for each point of the linear transect, similar to the methodologies used by the USVI Territorial Coral Reef Monitoring Program (TCRMP) and Atlantic and Gulf Rapid Reef Assessment (AGRRA) (Calnan 2008; Smith et al. 2008). Notations could include "no mortality", "partial mortality", and "substantial mortality" as well as an indication of old or recent mortality. Diseased colonies could be noted for the points of the linear transect and for the broader survey area. TCRMP categorizes disease into recognized Caribbean scleractinian diseases and syndromes that included bleaching, black band disease, dark spots disease, white plague, and yellow band (blotch) disease), and most recently the Stony coral tissue loss disease (SCTLD).

These indicators could be used as metrics to highlight vulnerable reef conditions that might be worsening. In developing the BSAT, the DEMO measures of percent mortality and number of diseased colonies were tested. These rules were not incorporated into the screening tool because they did not improve discrimination between BCG Levels and might not be consistently estimated.

Additional considerations included presence of scleractinian ESA taxa, and fish diversity and abundance. Presence of a high number of ESA taxa might indicate that the reef is not severely degraded. Absence or paucity of fish might indicate that the reef is moderately or severely degraded. These measures were not included in the BSAT but could add additional interpretive information for a screening-level assessment.

For the draft screening-level evaluation, quantitative rules were established using distributions of the metrics as guides for establishing thresholds (**Table 12**). The primary threshold for finding a difference between "Good-Fair" conditions and "Poor-Very Poor" conditions was similar to the threshold between BCG Levels 4 and 5 of the full first generation BCG benthic model. Using this threshold, the screening model predicted the same condition as the experts for 83% of the sites including all rated sites (calibration and validation). Additional thresholds were described for estimation of differences between "Good" and "Fair" conditions (similar to Levels 3 and 4), and between "Poor" and "Very Poor" conditions (similar to Levels 5 and 6). There was more disagreement among the secondary threshold conditions and the overall correct agreement within the four condition Levels was 70%.

Table 12. Benthic Screening Assessment Tool rules (first generation). The primary thresholds are those described at the Fair Level. A Very Poor assessment would result from sites that do not meet the Poor thresholds.

Comparable BCG Level	Good (Level 3 and above)	Fair (Level 4)	Poor (Level 5 and below)
LPI % coral cover	>20 (15-25)	>10 (5-15)	>4 (0-8)
% *Orbicella* and *Acropora* cover	>6 (2-10)	>1 (0-2)	
Non-tolerant taxa richness	>2 (1-3)	>1.5 (0-3)	>1 (0-2)
% bare substrate and turf algal cover with sediment	<40 (30-50)	<50 (40-60)	<60 (50-70)

Fish BCG Model

Why fish?

Fish assemblages can be integral components of coral reef ecosystems and are indicators of reef ecosystem condition. The benthic organisms (e.g., stony corals, gorgonians, and sponges) and adjacent habitats (e.g., seagrass meadow and mangrove forests) provide critical nurseries, foraging areas, habitat, and refugia for fish (Nagelkerken et al. 2000; Christensen et al. 2003; Mumby et al. 2004, 2008; Adams et al. 2006; Cerveny 2006; Dahlgren et al. 2006; Aguilar-Perera and Appeldoorn 2007; McField and Kramer 2007; Meynecke et al. 2008; Clark et al. 2009; Pittman et al. 2010). Reef fish abundance and diversity are associated with reef habitat structure, complexity, and quality, and can therefore be indicators of reef condition (Gladfelter et al. 1978; Carpenter et al. 1981; Bell and Galzin 1984; Sano et al. 1984; McClanahan 1994; Caley and St. John 1996; Ormond et al. 1996; Lewis 1997a, b 1998; Williams 1991; Warren-Rhodes et al. 2003; Lindberg et al. 2006; Bejarano-Rodríguez 2006; Wilson et al. 2006; Alvarez-Filip et al. 2009; Walker et al. 2009; Pittman et al. 2007a, b; Brandt et al. 2009).

Reef fish have diverse functional roles that are essential to coral reef integrity. For example, herbivores control algae that may otherwise replace living corals (Hughes 1994; Burkepile and Hay 2008). Large piscivores provide top-down control of the fishes that prey on herbivores (Mumby et al. 2006; Stallings 2008, 2009), and help to control the abundance of coral feeders and bioeroders (Bradley et al. 2020). Additionally, reef fish provide economic and cultural value (e.g., food provisioning via subsistence and commercial fishing) and support tourism and recreational activities (Pendleton 1995; Hawkins and Roberts 2004; Principe et al. 2012; Brander and van Beukering 2013; Spalding et al. 2017). Given their diverse functional roles in the ecosystem and their societal value, using reef fish as indicators of coral reef ecosystem condition can help managers to set targets for protection and restoration of coral reefs (Bradley et al. 2020).

Fish Data

EPA 2010 and 2011 survey data for southern Puerto Rico were subjected to thorough QA/QC to eliminate uncorrectable, unmatched, or conflicting data, sites deemed to be in non-target habitat types, and to correct older taxonomic names or synonyms. The data were then put into an Excel workbook for use by the experts. The workbook included a series of linked worksheets, including:

- Notes with descriptions of the other worksheets and metadata
- A Status Page with a summary of sites and expert consensus BCG Level assignments
- A data taxa master worksheet that provides species information, including scientific and common names, classification, BCG attribute, trophic guild, whether large or small for important targeted species, preferred habitat (Humann and DeLoach 2003), tolerance to sediment, fishing pressure
- A data habitat worksheet, that provides other information by site (e.g., exercise ID, survey index, collection date, collection method (EPA, NCRMP, RVC), region, latitude/longitude, survey year, whether in an MPA, habitat (NOAA benthic maps), etc.)
- Data sheets from individual monitoring sites, including site and sample information (see **Figure 25**.)

ExerciseID	Samp0007	Best Tier	2	Assigned Tier	Reasoning	
Collection Date	11/29/2011	Median Tier	3	3		
Collection Metho	USEPA	Worst Tier	3	reef		

TAXA SUMMARY

BCG Attribute	Number of Taxa	Density (100-m²)	Biomass (kg/km²)	Pct Taxa	Pct Density	Pct Biomass
1	0	0	0.0	0%	0%	0%
2	1	6	3,574.2	5%	3%	2%
3	9	143	130,342.2	43%	77%	81%
4	9	33	25,117.0	43%	18%	16%
5	0	0	0.0	0%	0%	0%
6	0	0	0.0	0%	0%	0%
x	2	4	1,676.8	10%	2%	1%
Total	*21*	*186*	*160,710.2*	*100%*	*100%*	*100%*

TAXA LIST

BCG Attribute	Common Name	Scientific Name	Density (100-m²)	Biomass (kg/km²)	Family	TaxaMap
3	blackbar soldierfish	Myripristis jacobus	1	1,068.9	Holocentridae	map
4	ocean surgeonfish	Acanthurus bahianu	2	2,574.1	Acanthuridae	map
3	doctorfish	Acanthurus chirurgu	81	95,150.4	Acanthuridae	map
2	blue tang	Acanthurus coerule	6	3,574.2	Acanthuridae	map
4	redlip blenny	phioblennius maccl	2	171.0	Blenniidae	map
x	bar jack	Carangoides ruber	1	337.8	Carangidae	map
4	french grunt	aemulon flavolineat	1	1,109.4	Haemulidae	map
3	Spanish hogfish	Bodianus rufus	3	3,756.8	Labridae	map
3	clown wrasse	lichoeres maculipe	2	629.6	Labridae	map
x	blackear wrasse	Halichoeres poeyi	3	1,338.9	Labridae	map
3	bluehead wrasse	alassoma bifasciatu	50	964.6	Labridae	map
3	schoolmaster	Lutjanus apodus	2	8,640.8	Lutjanidae	map
4	yellowtail snapper	Ocyurus chrysurus	2	1,661.4	Lutjanidae	map
4	spotted goatfish	eudupeneus macula	2	2,176.6	Mullidae	map
4	sergeant major	Abudefduf saxatilis	1	449.6	Pomacentridae	map
3	yellowtail damselfish	rospathodon chrys	2	3,239.4	Pomacentridae	map
4	dusky damselfish	Stegastes adustus	17	2,829.6	Pomacentridae	map
4	redband parrotfish	arisoma aurofrenat	3	5,797.0	Scaridae	map
4	yellowtail parrotfish	parisoma rubripinn	3	8,348.4	Scaridae	map
3	stoplight parrotfish	Sparisoma viride	1	1,510.9	Scaridae	map
3	great barracuda	Sphyraena barracud	1	15,380.9	Sphyraenidae	map

STATION AND SAMPLE CHARACTERISTICS

StationID	PR11-55
Region	Jobos
Latitude	17.9116
Longitude	-66.2303
Reef Type	Linear Reef
Habitat	Coral Reef and Colonized Hardbottom
Depth (Coral, m)	19
Distance (shore, km)	2.78
Distance (shelf, km)	1.74
Distance (disturbance)	
Sediment Threat	
Rugosity Index (EPA) (m)	1.688
Diadema (100 m²)	0
Coral Density (m²)	3.08
Height_sd	23.90
Coral_2D_Cover_Live	0.143
Coral_Richness_Live_Transect_Area	12
CSA Total Live (3D)	17494.0
CSA Total Live (3D) m²	3359.0
Num Acroporids	1
Num massive colonies (Orbicella)	1
Sponge Density (m²)	NA
Gorgonia Density (m²)	3.8
Sponge Morph Richness (5m²)	0
Gorgonia Morph Richness (5m²)	4
Fish, Richness (100-m²)	21
Fish, Density (100 m²)	186
Fish, Length (mean, cm)	13.0
Fish, Length (std dev, cm)	22.7
Fish, Total Biomass (kg/km²)	160710.2
Fish, Number of Schools	2
Acanthuridae(Tangs, Doctor and Surgeo	47.8%
Scaridae & Sparosomids(Parrotfish both	3.8%
Chaetodontidae (Butterfly fish)	0.0%

Figure 25. Screenshot of Fish data sheet (MS Excel). This view shows the site and sample characteristics on the right side, and the taxa list on the left side, including the assigned BCG attribute, common name, scientific name, density, biomass, and family.

Considerable information was provided to the experts for each site. Basic information included the site ID, collection date, region, and locational information (lat/long). Additional information useful for rating the sites included:

- **Depth**. Roberts and Ormand (1987) stated that depth alone can be a good indicator of fish species richness. Additionally, depth is a defining variable for reef type (Walker et al. 2009).

- **Distance from Shore.** Distance from shore was a surrogate for sediment stress. It is particularly important because certain fish species use near-shore habitats as nurseries prior to moving out to adult reef habitats (Appeldoorn et al. 1997, 2003; Lindeman et al. 2000; Nagelkerken et. al 2015; Dahlgren and Eggleston 2000; Cocheret de la Morinière et al. 2002a, b; Christensen et al. 2003; Aguilar-Perera 2004; Mumby et al. 2004, 2008; Aguilar-Perera and Appeldoorn 2007; McField and Kramer 2007; Meynecke et al. 2008; Sale et al. 2010, Schärer-Umpierre 2009).

- **Distance from Shelf Edge**. Shelf breaks are areas of unique habitats and physical properties (Scherbina et al. 2008) that support distinctive fish assemblages (Kimmel 1985, Cerveny 2006, Pittman et al. 2010). Additionally, they are an important spawning habitat for a variety of species (Thompson and Munro 1974; Johannes 1978; Colin et al. 1987; Shapiro et al. 1993; Sadovy et al. 1994a, b; Sala et. al 2001; Claro and Lindeman 2003; Nemeth et al. 2006; Ojeda-Serrano et al. 2007a, b; Heyman and Kjerfve 2008; Schärer-Umpierre 2009; Schärer et al. 2014).

- **Reef Type**. Reef types were based upon the benthic classification (Kendall et al. 2001). Classifications for Coral Reef and Hardbottom, were further delineated as either Coral Reef and Colonized Hardbottom or Uncolonized Hardbottom Reef Rubble. Within the Coral Reef and Colonized Hardbottom category, there were seven possible habitats: Linear Reef, Spur and Groove, Individual Patch Reef, Aggregated Patch Reefs, Scattered Coral/Rock in Unconsolidated Sediment Colonized Pavement, Colonized Bedrock and Colonized Pavement with Sand Channels. Within the Uncolonized Hardbottom Reef Rubble category there are three possible habitats: Uncolonized Pavement, Uncolonized Bedrock and Uncolonized Pavement with Sand Channels.

- **Rugosity.** The rugosity index provides an estimate of reef topographic complexity. In the EPA dataset, rugosity was measured using the chain-and-tape method (McCormick, 1994): a ratio of the length of a chain draped across the reef surface to the linear stretched length (Hobson1972; McCormick 1994; Rogers et al. 1994; Lang 2003; Santavy et al. 2012). A strong positive correlation between topographic complexity and reef fish abundance, biomass, and/or species richness has been documented (Talbot 1965; Talbot and Goldman 1972; Risk 1972; Luckhurst and Luckhurst 1978; McClanahan 1994; McCormick 1994; Green 1996; Appeldoorn et al. 1997; Friedlander and Parrish 1998; Friedlander et al. 2003; Gratwicke and Speight 2005a and 2005b; Kuffner et al. 2007; Pittman et al. 2007a; Walker et al. 2009). Reef flattening, the reduction in the amount and complexity of reef structure resulting from physical destruction and erosion of stony corals, has resulted in the loss of species richness and abundance of reef fishes and invertebrates (Gratwicke and Speight 2005b; Idjadi and Edmunds 2006; Wilson et al. 2007).
- **Three-dimensional habitat.** Whereas the rugosity index accounts for important vertical dimensions, it does not fully reflect the three-dimensional availability of fish habitat. Therefore, the data also included additional indicators of available habitat, such as 3D colony surface area estimates for the three major sessile benthic populations, stony corals, sponges, and gorgonians (Courtney et al. 2007; Santavy et al. 2012; Fisher et al. 2007, 2014). (See benthic chapter for more discussion of these metrics).

Fish Assemblage Calculated Metrics. Commonly used metrics about the fish assemblage were calculated, including fish species richness, density, fish length mean and standard deviation, total fish biomass, number of fish schools, percent of fish in various families, *Acanthuridae*, *Scaridae*, *Chaetodontidae*, *Haemulidae*, *Pomacentridae*, *Labridae*, *Lutjanidae* and *Carangidae* and *Serranidae*, and relative biomass of herbivores and piscivores (Caldow et al. 2009; Santavy et al. 2012).

Fish Species Information. The list of fish species observed at the site was provided, including density and biomass by species, and BCG attribute assignments. Summary information, organized by BCG attribute, was provided including the number of taxa, density and biomass, the percent of the taxa, density and biomass, and totals for number of taxa, density and biomass. Note: Cryptic species are present at sites, but not easily detectible in fish surveys.

Fish BCG Attributes

As a first task, the fish experts identified the stressors most relevant to fish assemblage condition as habitat degradation, sediment stress, and fishing pressure (Bradley et al. 2016). The experts used the BCG attribute definitions (**Appendix B**), their expert knowledge and experience, available literature, and frequency of a species occurring in the data set to assign 357 Caribbean fish species to the taxonomic attributes (attributes I–V) based on their sensitivities to two anthropogenic stressors (sediment and fishing).

Non-native species were identified as BCG Attribute VI, reflecting the detrimental effects of nonnative taxa on native species (Davies and Jackson 2006; EPA 2016). Some taxa were assigned an "x" because the fish experts were unfamiliar or had little supporting information in the literature relative to stressor tolerance to assign them to a BCG attribute, or because the survey methodology did not allow an accurate count of the species (e.g., cryptic species). The list of species with their assigned attributes is provided in **Appendix O**. Four fish species are listed under the ESA, *Epinephelus striatus* (Nassau Grouper) and *Manta birostris* (Giant Manta Ray), *Sphyrna lewini* (Scalloped Hammerhead Shark - Central and Southwest Atlantic Distinct Population Segment), and *Carcharhinus longimanus* (Oceanic Whitetip Shark) (**Table 13**).

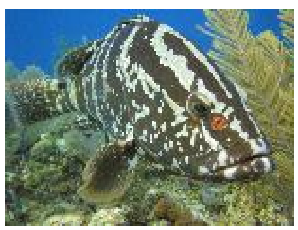
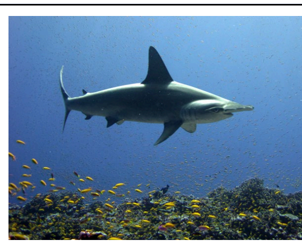
For fishing pressure, the fish experts considered whether each species was subject to fishing pressure and the degree of that pressure, the category of fishing pressure (e.g., commercial, recreational, or ornamental), and whether that species was regulated under federal or territorial fishing laws (EPA 2016).

Because there is limited literature on reef fish species' sensitivity to sediment stress, the experts considered life-history characteristics (e.g., ontogenetic migrations between habitats) as well as personal observations of a species in turbid waters, very clear waters, or both.

The experts assigned fish to Attributes I – VI with the following frequency:

- Attribute I: Historically Documented, Long-lived, or Regionally Endemic Taxa – 15 taxa
- Attribute II: Highly Sensitive Taxa - 54 taxa
- Attribute III: Intermediate Sensitive Taxa – 108 taxa
- Attribute IV: Intermediate Tolerant Taxa - 51 taxa
- Attribute V: Tolerant Taxa - 4 taxa
- Attribute VI: Non-native or Intentionally Introduced Taxa - 3 taxa
- X – Taxa not assigned to an attribute – 122 taxa.

Table 13. Caribbean fish species listed as threatened under the U.S. Endangered Species Act.

Scientific Name Common Name	Photograph	*Scientific Name* Common Name	Photograph
Epinephelus striatus Nassau Grouper		*Manta birostris* Giant Manta Ray	
Sphyrna lewini (Scalloped Hammerhead Shark		*Carcharhinus longimanus* (Oceanic Whitetip Shark)	

Assignment of BCG Levels to Sites and Preliminary Narrative

Model Development

The second task for the fish experts was to assign BCG Levels to individual sites based on natural site classification and species composition. A set of 38 sites was selected from the EPA 2010/2011 surveys that spanned the range and gradient of sediment stress that occurs in south-western Puerto Rico. These were not necessarily the same sites as were used in the benthic narrative model development. In a workshop setting, the panel facilitator projected the data for each site onto a screen and presented the site data and summary metrics. The experts were asked to consider a site then document their recommended BCG Level, the critical or most important information they used to inform the decision, any confounding or conflicting information, and how they resolved these conflicts (EPA 2016; Gerritsen et al. 2017). The facilitator then called on each expert to present their rating and rationale, capturing the information in the projected BCG workbook.

Once all experts had provided their individual ratings, the experts discussed the ratings and rationales and revised their individual ratings if new information or insight caused them to evaluate the site differently. The experts felt that the group discussions and ability to share knowledge with each other was important. The median score was proposed as the site rating, and experts were asked to concur in a final rating for the site. Rationale for the rating was then documented.

The experts agreed that all sites had some degree of disturbance, including ubiquitous effects from fishing pressure, reef degradation, and turbidity from terrigenous sediment. The experts did not assign any sites to BCG Levels 1 or 2. All sites were rated as BCG Levels 3-6.

Next the fish experts provided narrative statements to describe what they expected to see for each BCG Level starting from the highest quality condition observed in the data set. This narrative became the basis for BCG rule development. The fish experts developed conceptual rules for Level 2, as was done by the benthic experts.

The experts identified a set of metrics that they used to distinguish BCG Levels, including taxa richness total biomass, sensitive taxa, density of damselfish, piscivores, and other fishes. Based upon the analysis, a set of draft narrative fish rules was developed by the experts. These narrative Level descriptions were qualitative (e.g., high diversity, reduced diversity). The narrative decision rules exhibited a general pattern of decreasing richness and biomass, especially of sensitive or specialist fish, as biological condition degrades (**Table 14)**.

Table 14. Narrative rules for fish BCG Levels in Puerto Rico coral reefs

Level	Narrative Rule
BCG Level 1	Populations have balanced species abundance, sizes, biomass, and trophic interactions; Large piscivores present (groupers, barracuda, and sharks)
BCG Level 2	Populations have balanced species abundance, sizes, biomass, and trophic interactions; Large piscivores present (groupers and snappers, but not sharks); schools of piscivores present *
BCG Level 3	Decline of large apex predators (e.g., groupers, snappers, etc.) noticeable, however still present; small reef fish more abundant than Levels 1–2; large body parrotfish present; high within-family diversity
BCG Level 4	Near absence of large piscivores, however at least one piscivore present; small reef fish abundant (mostly damselfish and wrasses); parrotfish present
BCG Level 5	No large fish, few intolerant species, lack of multiple trophic levels; more than 4-5 fish species
BCG Level 6	Does not meet Level 5 rules

* The fish experts felt that it was important to separate sharks out from other large predators. The long history of shark exploitation makes it difficult to accurately characterize the role of sharks on coral reefs, because fishing has selectively removed larger, older individuals, causing mean sizes to decline (Anderson et al. 2008; Barley et al. 2020). However, sharks most certainly function as either transient apex predators or reef-associated mesopredators (Frisch et al. 2016; Roff et al. 2016; Desbiens 2021), directly impacting the demography of many reef fish (DeMartini et al. 2008; Stallings 2008).

Numeric Model – Calibration and Validation

The fish experts' narrative rules and reasoning, both quantitative and qualitative, were compared to data summaries of the sites evaluated by the experts. For example, if the experts identified a small to moderate number of sensitive taxa for BCG Level 3, then the number of sensitive taxa in sites the panel assigned to BCG Level 3 were examined (e.g., sensitive taxa ranged from 4-8 in all sites assigned to BCG Level 3). Box plots were developed for each of the experts' narrative statements (**Figures 26-28**), which informed thresholds for the numeric rules. Opinions repeatedly expressed by the experts that were not included in the draft narrative rules were used to formulate additional rules. Some rules suggested by the panel (e.g., species per family in Levels 3 and 4; damselfish and wrasses in Level 4; and piscivores in Level 4) either did not discriminate between Levels or were redundant with other rules and therefore were not included in the final rules.

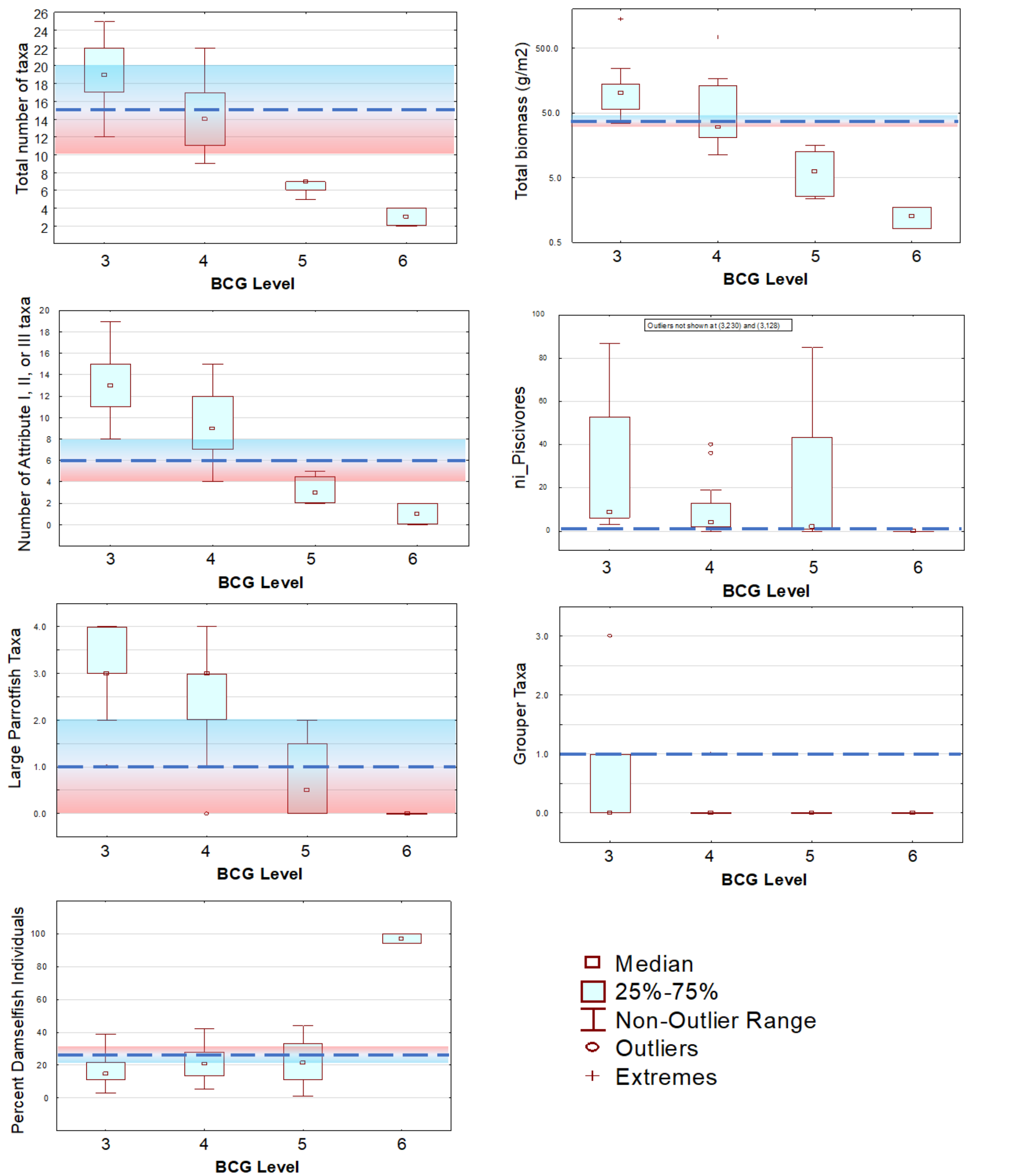


Figure 26. Diagrams of fish rules (Y axis) for Level 3, showing metric distributions for sites as rated by the experts (BCG Levels; X axis) showing rule thresholds (dashed lines) and threshold ranges (shaded box). Membership values are calculated as 1.0 if the metric value is better than the blue range, 0.0 if worse than the red region, and interpolated between 0.0 and 1.0 if within the shaded region. Distributions include the median (central square), intraquartile range (rectangular box), non-outlier ranges (whiskers), and outliers (circular marks).

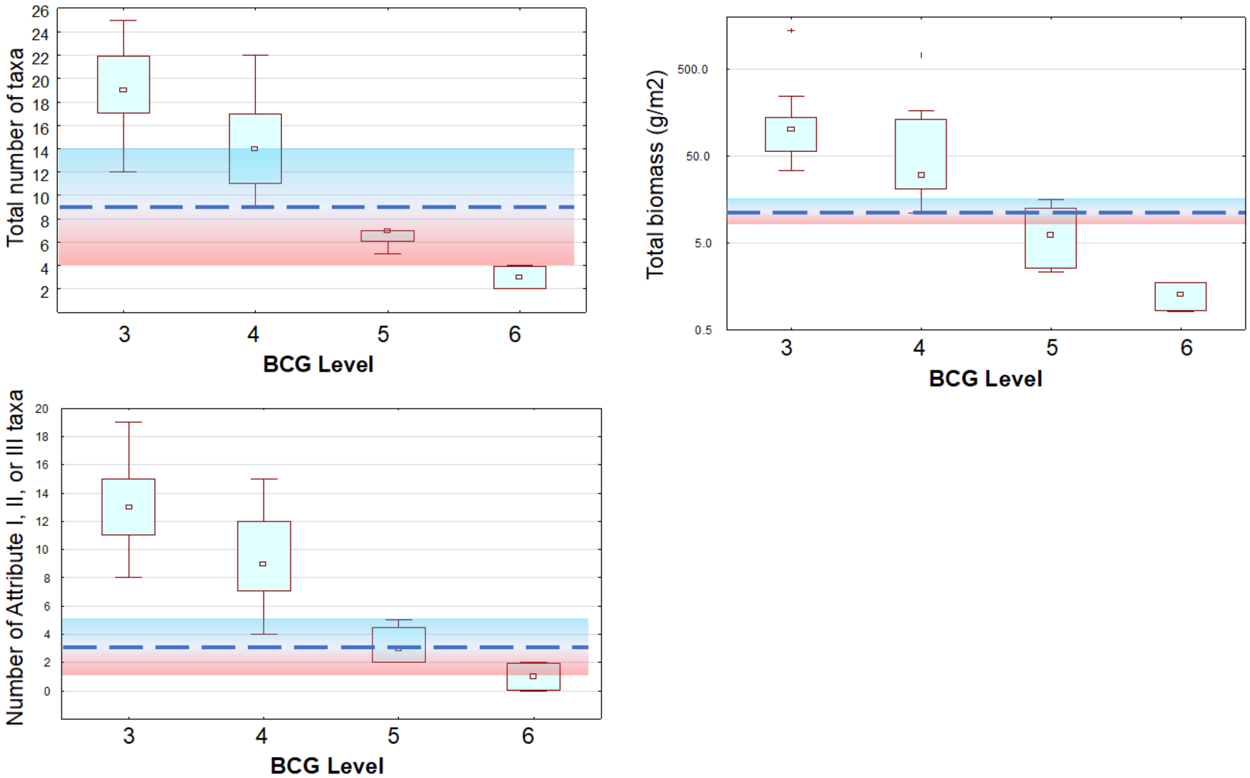


Figure 27. Distribution of metrics used in model rules for discriminating Fish BCG Levels 4 and 5, showing the rule thresholds (dashed line) and ranges (color-shaded region). Membership values are calculated as 1.0 if the metric value is better than the blue range, 0.0 if worse than the red region, and interpolated between 0.0 and 1.0 if within the shaded region. Distributions include the median (central square), intraquartile range (rectangular box), non-outlier ranges (whiskers), and outliers (circular marks).

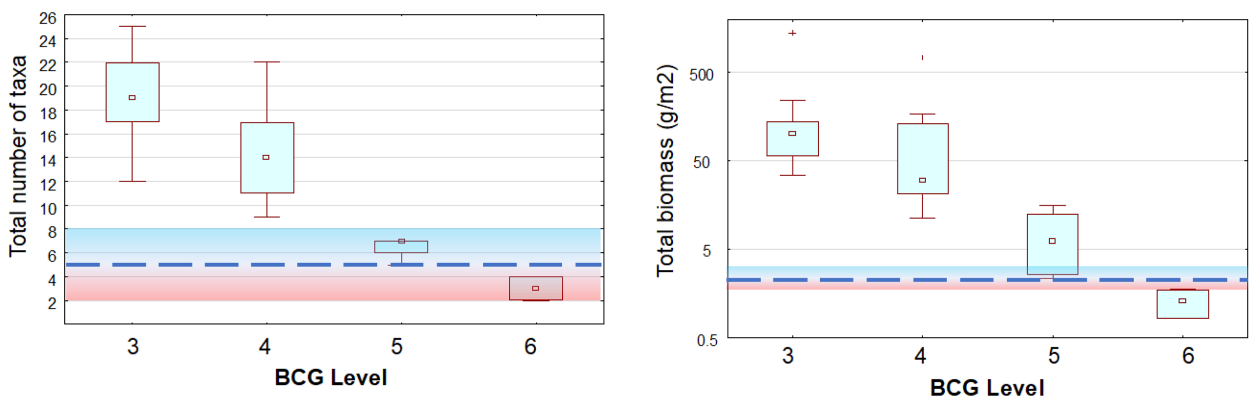


Figure 28. Distribution of metrics used in model rules for discriminating Fish BCG Levels 5 and 6, showing the rule thresholds (dashed line) and ranges (color-shaded region). Membership values are calculated as 1.0 if the metric value is better than the blue range, 0.0 if worse than the red region, and interpolated between 0.0 and 1.0 if within the shaded region. Distributions include the median (central square), intraquartile range (rectangular box), non-outlier ranges (whiskers), and outliers (circular marks).

The fish experts had different expectations for fish assemblages in reef habitat than in other colonized hard-bottom habitats. Colonized hard bottom is characterized as mixed communities of algae, sponges, octocorals and stony corals. While hard bottom can support coral communities, they generally lack the coral diversity, density, and reef development of patch and outer bank reefs. Adjustments were made to the rules by the experts based on their knowledge and field experience studying these two different coral habitats. Seven decision rules were developed for BCG Level 3; any six of the seven rules must be met to assign BCG Level 3 in reef habitat, while five must be met in colonized hard-bottom habitats.

The draft BCG decision model was applied to the 38 original sites and those results were compared to the expert BCG Level ratings for the same sites. The quantitative model was 92% accurate (90% confidence interval: 81 – 98%) in replicating the expert panel assessments within one-half BCG Level for the calibration dataset (**Table 15**). When there was a discrepancy (3 sites), it was never more than one Level of difference, and occurred at the threshold between BCG Levels 3 and 4. **Figure 29** shows the distribution of individual panelist scores compared to the group median for each site. Because of the expected variability in a natural system, the experts did not consider a half-Level mismatch (a comparison including a tie level) with their consensus to be a meaningfully different assessment, and a half-Level was similar to the spread in ratings among experts. The experts assigned individual ratings that were within one third of the group median BCG Level for 85% of individual assessments. That is a difference of a "+" or "-" rating, as described in the benthic Numeric Model.

The next step was to confirm (validate) the model with new (not previously rated) sites. The experts reviewed 11 validation sites, applied the numeric fish rules to assign a BCG Level to each site, and stated reasons if they disagreed with any given quantitative rule. No disagreements with rules were stated and the experts completed the validation sites. Accordingly, the experts did not adjust ratings or modify rules for small mismatches. There were, however, several issues that arose that warrant further investigation (see Future Research Section). The quantitative model was 82% accurate (90% confidence interval: 53 - 97%) for the validation dataset (**Table 16**). The experts' ratings for the validation sites were mostly close to the group median, with 78% of individual ratings within one third of the BCG Level of the panel median (**Figure 29**).

Table 15. Comparison of expert ratings of BCG Levels for fish calibration reef sites compared to BCG Levels predicted by the model, showing where there was agreement (shaded cells) and disagreement (unshaded cells).

			BCG Model Predictions – Fish Calibration							
	Rating	Total # Rated	2	3	3-4 tie	4	4-5 tie	5	5-6 tie	6
Expert BCG Assignment	2	0	0	0	0	0	0	0	0	0
	3	14	0	11	2	1	0	0	0	0
	3-4 tie	1	0	0	0	1	0	0	0	0
	4	16	0	2	0	13	1	0	0	0
	4-5 tie	1	0	0	0	0	1	0	0	0
	5	4	0	0	0	0	0	3	1	0
	6	2	0	0	0	0	0	0	0	2

Table 16. Comparison of expert ratings of BCG Levels for fish validation reef sites compared to BCG Levels predicted by the model, showing where there was agreement (shaded cells) and disagreement (unshaded cells).

			BCG Model Predictions – Fish Validation							
	Rating	Total # Rated	2	3	3-4 tie	4	4-5 tie	5	5-6 tie	6
Expert BCG Assignment	2	0	0	0	0	0	0	0	0	0
	3	9	0	7	0	2	0	0	0	0
	3-4 tie	1	0	1	0	0	0	0	0	0
	4	1	0	0	0	1	0	0	0	0
	4-5 tie	0	0	0	0	0	0	0	0	0
	5	0	0	0	0	0	0	0	0	0
	6	0	0	0	0	0	0	0	0	0

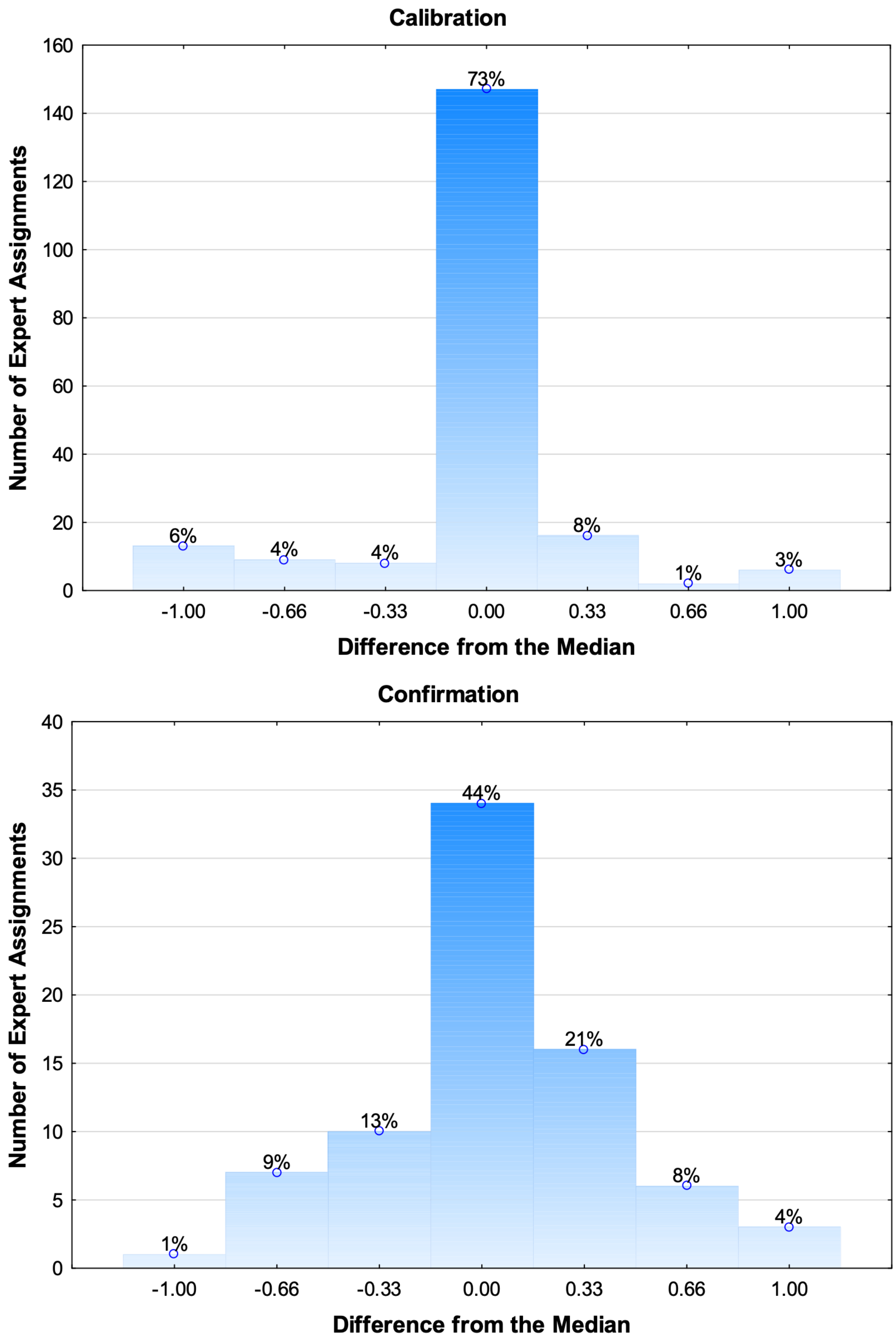


Figure 29. Distribution of fish panelists' BCG Level assignments expressed as difference from the group median in 1/3 BCG Level steps. Calibration (top) and confirmation (bottom) sites from the Puerto Rico reef fish dataset.

Transferability to Another Region

As an exploratory test of model transferability to other coral reef fish communities, the fish experts rated 14 sites collected using RVC methods in the Florida Keys and Dry Tortugas from 2014-16 at depths shallower than 16 m. A reference dataset was used to establish "recent best" condition (e.g., low stressor levels, water quality and fishing impacts): RVC surveys conducted in Dry Tortugas National Park, depths < 16m, during years 2011-2016 (surveys in 2011, 2012, 2014, 2016). This period encompasses recent surveys, conducted well after a period of intense hurricanes (2004-2005) and implementation of large Marine Protected Areas (MPAs; 2001 in Tortugas Bank and Riley's Hump, 2007 in Dry Tortugas National Park). For the reference dataset, the RVC leads computed richness, total fish density, large piscivore density for each site (100 x 100 m grid cell, 2 sites, 2 divers each site). All three metrics showed increasing median/mean values with increasing rugosity category. Richness showed the best discrimination by rugosity. The RVC leads computed mean and standard deviation of each metric for each habitat type (Low-, Mid-, High-Relief). These were used to 'standardize' the site-specific metrics for the workshop dataset (2014-16 fish-coral sites).

The sites were selected by the RVC leads to reflect a stressor gradient for both fishing and land-based pollution. Four zones were identified, with three sites selected from each zone; one from the upper end of the standardized richness distribution, one from the middle, and one from the lower end; 12 sites total. The Dry Tortugas was the best representation of an undisturbed reference region with respect to WQ and fishing impacts, in the Florida Keys. Two sites were selected from the upper end of the richness score distribution from the Dry Tortugas sites to provide a starting point for the workshop exercise reflecting the high-end of fish assemblage metrics for judging sites from other areas a total of 14 sites were used for the workshop.

The quantitative BCG model developed for Puerto Rico was 79% accurate in replicating the expert panel assessments within one-half BCG Level for the Florida Keys calibration. The biomass metric was the rule that was not met in the mismatched sites. The experts felt that species attribute assignments might need to be revisited based on location, particularly because fishing pressure varies significantly by jurisdiction.

Fish Model Rules

The BCG model has been successfully adapted to accommodate fish in coral reef ecosystems while maintaining the model's conceptual integrity (**Table 17**). A regional panel of experts assigned fish species inhabiting Puerto Rico's near-shore linear coral reefs to attributes of sensitivity to human disturbance, natural prevalence, historic species importance in the Caribbean, and native or non-native origin. The experts developed fish rules for six Levels of coral reef condition, with a well-defined narrative for each Level.

Table 17. BCG reef fish assemblage decision rules. Numbers in parentheses are lower and upper bounds for group membership. Puerto Rico rules are based on 4 m x 25 m belt transect data collected during 2010-2011 (Santavy et al. 2012). Florida rules are based on 15 m diameter cylinder RVC point count data (Smith et al. 2011) collected during 2014-2016. Continued on following pages.

BCG metric	Narrative rules	Quantitative rules
BCG Level 2 (No survey sites were identified, rules are conceptual)		
Total taxa	Richness is high – valid taxa only [a]	≥ 20 (15 - 25) taxa
Rare, endemic and special species (Attribute I species)	Present	≥ 1 taxon
Highly sensitive taxa (Attribute II species)	Present	≥ 1 (0 - 2) taxon
Proportion of all sensitive taxa (Attribute I, II, and III species)	Sensitive taxa constitute a large proportion of species richness	≥ 50% taxa (45 - 55)
Total biomass	High fish biomass – valid taxa only [a]	Puerto Rico: ≥ 65 (50 – 80 g/m^2) [b] Florida: ≥65 (51 – 79 g/m^2)
Large groupers	Present (*Epinephelus* and *Mycteroperca*)	≥ 1 (0 - 1) individual
Large predators [c]	Present	≥ 1 (0 - 2) individual
Piscivore individuals	Abundant	≥ 20 individuals
BCG Level 3 (reef habitat - must meet 6 of 7 rules; hardbottom habitat – must meet 5 of 7 rules)		
Total taxa	Richness moderate to high – valid taxa only [a]	≥ 15 (10 - 20) taxa
Number of all sensitive taxa (Attribute I, II, and III species)	Sensitive taxa are a small to moderate proportion of fish species richness	≥ 6 (4 - 8) taxa
Total biomass (g/m^2)	Total fish biomass is moderate to high – valid taxa only [a]	Puerto Rico: ≥ 35 (30 – 40 g/m^2) [b] Florida: ≥37 (32 – 42 g/m^2)
Piscivores	Presence of snappers or other piscivores	≥ 1 individual

BCG metric	Narrative rules	Quantitative rules
Parrotfish	Presence of large parrotfish [d]	≥ 1 (0 - 2) individual
Damselfish	Damselfish individuals are not dominant	< 25% individuals (20 - 30)
Groupers	Groupers present (*Dermatolepis, Epinephelus, Mycteroperca,* and *Cephalopholis*)	≥ 1 individual
Rule application: [e]	Reef Habitats: More stringent requirements Hard-bottom Habitats: Less stringent requirements	Require 6 of 7 rules Require 5 of 7 rules
BCG Level 4		
Total taxa	Richness low to moderate – valid taxa only [a]	≥ 9 (4 - 14) taxa
Number of all sensitive taxa (Attribute I, II, and III species)	Some sensitive taxa	≥ 3 (1 - 5) taxa
Total biomass (g/m^2)	Low or higher – valid taxa only [a]	Puerto Rico: ≥ 11 (7 – 15 g/m^2) [b] Florida: ≥ 6.2 (4 – 8.4 g/m^2)
BCG Level 5		
Total taxa	Sparse – valid taxa only [a]	≥ 5 (2 - 8) taxa
Total biomass (g/m^2)	Very low – valid taxa only [a]	Puerto Rico and Florida: ≥ 2 (1 – 3 g/m^2)
BCG Level 6	Does not meet Level 5 rules	

a. Valid taxa are those that were expected to be consistently sampled. They did not include taxa with attribute x-MNS (method not suitable) or with attribute x-NRF (not a reef fish).
b. Because of differences in sampling protocols, the calculation of biomass differs between Puerto Rico (including the U.S. Virgin Islands) and Florida.
c. Large predators include groupers, sharks, snappers, jacks, tarpon, and barracuda.
d. Large parrotfish include all taxa in the Scaridae family.
e. For Level 3, rules can be discounted depending on the habitat type. For reef habitats, the highest 6 rule results are considered, discounting the rule resulting in the lowest membership value. For hard-bottom habitats, the lowest 2 membership values can be discounted.

Fish Model Discussion

The fish BCG model can be used to quantitatively interpret Caribbean reef condition for conditions ranging from BCG Level 3 to BCG Level 6. The model was based on expert-derived numeric decisions rules. BCG Level 1 was not expected to occur in Puerto Rico or the USVI because of the impacts of habitat destruction from intense land-based activities and fishing pressure over the past 50 years. No Level 2 conditions were observed; however, conceptual Level 2 rules were proposed based on experience and knowledge of historical descriptions.

Some rules were specific for a single Level but not for other Levels. For example, a rule that discriminated for Level 3 did not discriminate for Level 4 (e.g., percentage of damselfish; presences of piscivores, groupers and parrotfish) and therefore were not used except for Level 3 assignments. However, some rules were discriminatory along the full gradient and used to discriminate BCG Levels 3, 4 and 5. For example, the total taxa and total biomass rules discriminated for all Levels. Level 5 expectations were not very high. If there were at least some fish species observed, then the site was not relegated to the final lowest Level 6.

The fish BCG model (as developed for Puerto Rico) had a high degree of fidelity to the expert decisions: the model replicated the expert consensus within one BCG Level for 100% of sites and replicated the expert consensus within a half BCG Level for 82% (validation) to 92% (calibration) of the sites. This degree of predictive accuracy is as good as or better than that for freshwater systems (Gerritsen 2017; Hausmann et al. 2016). Given the variability in sampling fish assemblages, the experts considered a half-Level difference to be "splitting hairs".

An exploration of the model application to coral reef systems in other regions was tested using data from 14 sites in the Florida Keys and Dry Tortugas. The model was 79% accurate in replicating the expert panel assessments within one-half BCG Level for the Florida Keys calibration. The biomass metric was the rule that was not met in the mismatched sites, and the experts recommended further research to develop age/size class metrics for future updates to the BCG fish model. The experts also recommended that species attribute assignments be revisited based on location, particularly because fishing pressure varies significantly by jurisdiction.

The BCG fish model development, calibration, and validation were successful for Puerto Rico and the USVI, and the narrative model can be readily transferred to Florida. Some species assignments to BCG attributes may need to be revised due to differences in fishing regulations and the numeric rules may need to be calibrated for Florida. The BCG process is fully transferable to other regions. A Table listing the metrics used in the BCG fish model rules and ecological/biological importance of each metric is provided in **Appendix P**.

Evaluation of Sites using Both the Benthic and Fish Models

In a joint meeting, the experts applied the BCG rules for both assemblages at common sites. As an example, at one site the benthic organisms met the benthic level 3 rules, but the fish only met the fish Level 5 rules. The panel assessed the site as *degraded but with high potential for recovery of the fish population because important habitat and food for fish were present*. This might require a fisheries management action, perhaps establishment of a Marine Protected Area that would be closed to fishing.

Summary and Recommendations for Future Research

The BCG model initially developed and applied in stream ecosystems was successfully adapted to assess the condition of coral reef ecosystems while maintaining the model's conceptual integrity. The experts used bioassessment data and personal knowledge to develop quantitative decision rules to describe six Levels of coral reef ecosystem condition through an iterative process. The BCG Levels are biologically recognizable, measurable stages in the condition of coral reef ecosystems in response to increasing amounts of anthropogenic stress. The fish BCG model had a high degree of fidelity to the expert decisions. The model replicated the expert consensus within one BCG Level for 100% of sites and replicated the expert consensus within a half BCG Level for 82% to 92% of the sites (validation and calibration, respectively). These percentages of correct fish model predictions are associated with 90% confidence intervals of 53 - 97% and 81 – 98%, The benthic BCG model also showed high concordance between ratings and model predictions. The benthic model replicated the expert consensus within one BCG Level for 100% of sites and replicated the expert consensus within a half BCG Level for 84% to 89% of the sites (validation and calibration, respectively). These percentages of correct benthic model predictions are associated with 90% confidence interval: 74 – 92% and 69 – 98%, Because fish and benthic assemblages respond differently to stressors, they can be combined for a robust assessment of biological condition. Both models have a degree of predictive accuracy that is as good as or better than the examples described for freshwater systems (Gerritsen 2017; Hausmann et al. 2016).

The BCG framework documents experimentally established scientific knowledge and employs rigorous testing of empirical observations (Davies and Jackson 2006). The BCG model can support both regulatory and non-regulatory water quality and natural resource programs, including development of biocriteria. Numeric biocriteria coupled with biologically based aquatic life uses provide a direct measure of the aquatic resource that is being protected (e.g., coral reefs), complementing chemical and physical water quality criteria. To facilitate use by territorial and state water quality and natural resource managers, the BCG rule application will be automated, and clear instructions will be provided for each BCG rule. For example, the fish rule of "at least one large-bodied parrotfish species present" requires clarification of what scientists mean by "large-bodied parrotfish". A precise definition has been documented for each rule, and guidance material is being developed so the BCG models can be easily applied and interpreted.

The general steps for the application of the coral reef fish and benthic BCG models are to collect or select site data, calculate metrics, and apply BCG rules to assign a BCG Level to fish or benthic assemblage data. Sample collection would use protocols for collecting the BCG calibration data, including the limitations on site habitat type. Metric calculations would be derived from sample data, taxa lists, traits, attribute designations (**Appendices M and O**), metric calculation procedures (**Appendix G**), and descriptions in the model rules tables (**Tables 9, 12, and 17**). In future efforts, calculation procedures will be automated so that agencies will be able to enter data in tabular format to generate BCG model predictions. The automated calculation tool is planned for application using R-Shiny.

Although the BCG model was developed using data from Puerto Rico and the USVI, it is important to note that the BCG is a general framework that can be applied to other coral reef ecosystems, as demonstrated by using sites from the Florida Keys and Dry Tortugas to test the transferability of the numeric BCG fish model. Other states and territories would need to adapt it to their own coral reef habitat and biota and develop a numeric model specific to their jurisdiction. Broader application in the Caribbean or the Pacific will require additional focused study using many of the same analytical processes described in this report. After 2018, NCRMP switched the fish method from belt transect to RVC in USVI and PR, which will affect the comparability of fish data pre-2018 to fish data post-2018 in the Caribbean. The NCRMP fish experts are working on calibrations between the belt transect method and the RVC method.

The issues the expert panel recommended for further investigation could lead to model improvements and refinements. The issues are presented below with possible approaches for resolution. More detailed discussion and details are provided in **Appendix Q**.

1. Recommendations from the full group (both benthic and fish experts)

Field Method for Measuring Rugosity/Surface Structural Complexity. Both the fish and benthic expert panels agreed that the methods used to estimate coral reef coarse rugosity (Risk 1972; Rogers et al. 1994. Measured in US EPA data) and 3D surface microheterogeneity rugosity value (MRV) (Measured in NOAA NCRMP data) were inadequate. Neither provided a measure of topography that represented and correlated to the features most important to the fish, coral, or other sessile benthic organism (includes invertebrates and algae). The MRV estimated reef rugosity, as the difference between the lowest and highest points in a quadrat along the transect, averaged for all quadrats at a site (NOAA Coral Program 2014; NOAA NCRMP 2014 Puerto Rico). Both measures attempt to reflect the importance of the height of coral colonies above the substrate, how much reef structure is present, and its provision of potential habitat for fish and other invertebrates.

Despite the drawbacks with the metric, benthic experts agreed measures from a single transect or bioassessment census survey were not adequate to accurately characterize the rugosity, or to explain where and why reefs do or do not occur at a specified location. Identification of a robust and valid approach to measure this feature is a research need (Dustan et al. 2013). The goal is to capture a measure of rugosity that is useful to compare qualities important to both fish habitat usage and benthic structural architecture built by the sessile calcareous hard corals.

Undisturbed Baseline Conditions. The BCG should be calibrated with surveys from relatively less disturbed areas elsewhere in the Caribbean. Two potential approaches were identified: 1) conduct a new coral reef survey at a long-established and presumably effective marine reserve to define a less disturbed reference condition, and 2) explore coral reef monitoring program data from AGRRA, which has been collecting coral reef data from sites throughout the Caribbean since 1997 and NPS data collected in the USVI.

The Generalized Stressor Axis (GSA). Both expert panels discussed the development of a GSA for coral reefs and other coastal and marine habitats that combines land-based sources of pollution, fishing pressure, and global climate change-associated thermal anomalies. The GSA is represented as the x-axis of the BCG conceptual diagram (Figure 1) and it informs the shape of the stressor-response curve as well as allowing BCG Levels to be associated with disturbances. The BCG model for both assemblages was developed based on expert knowledge and data on taxa responses to stressors that are predominant in the coastal waters of Puerto Rico and U.S.V.I. such as elevated sea temperature, suspended sediment, and fishing pressure. Both panels recommended exploring the development of a GSA. EPA has begun work on this research effort (**Appendix R**). In addition to supporting coastal and marine BCGs, the GSA will be useful for a variety of management programs, including Clean Water Act enforcement, Coastal Zone Management Programs, and Fisheries Management.

Habitat Classification. A research project to develop and update a standard classification system and GIS dataset to describe and map coral reef ecosystems of Puerto Rico and the USVI for use in biocriteria reporting is proposed. The project would include Lidar, predicted background habitat conditions, or another approach to improve reef classification as well as reconnaissance dives to ground-truth and refine the potential classifications and maps.

Transferring the BCG to Other Regions. The fish BCG is transferrable to other regions. The next step would be to apply the benthic BCG to NCRMP data from Florida, which has similar species and reef conditions to Puerto Rico and the USVI. As evidence builds and model refinements occur for the first generation of the coral reef BCG models, it supports efforts to develop the

BCG for Hawaii and the Pacific territories, using the fundamental BCG approach and foundational models developed for Puerto Rico and the USVI.

2. Recommendations from the Fish Experts

Reconsidering Biomass: Age/Class Metrics for the Fish BCG. The BCG fish experts consistently expressed dissatisfaction with the fish biomass metrics and requested information about the size class frequency distribution (not just enumeration) of the fish observed. Enumeration of juvenile and adults (or size distribution based on maximum size for each species) for future rating exercises would allow calculation of life-stage metrics for reef fish. Associating the life stages with size ranges might allow better discrimination of BCG Levels and reveal areas of ontogenetic connectivity.

Ecosystem Connectivity - Seascape Ecology. Coral reefs are part of a tropical marine seascape that functionally links them with the adjacent shallow coastal habitats. Many reef fish respond to this spatial mosaic by showing pronounced associations with specific habitat types. Three types of future research were recommended by the fish experts: 1) high-resolution reef bottom topography (LIDAR or other) and habitat maps (such as are available for La Parguera) to allow for better estimation of connectivity, 2) application of landscape ecology methods to coastal and coral reef ecosystems to identify metrics that can be used to quantify BCG Attribute X – Ecosystem Connectivity, and 3) development of improved information on species and functional traits for Caribbean reef fish.

Ecological Traits for Caribbean Fish Species. Detailed information is needed about the life history, biological, ecological, and geographical characteristics of Caribbean fish species similar to that provided in Weil (2019; **Appendix S**) for Caribbean coral species.

3. Recommendations from the Benthic Experts

Increased replication of LPI Surveys. The LPI methodology is considered an economical time and cost-effective approach proven to be precise and highly accurate for measuring benthic cover (Beenaerts and Berghe 2005; Nadon and Stirling 2006) The benthic panel recommended using four to five 10m LPI transects and agreed a single 10m transect was insufficient to characterize reef condition or adequately determine benthic cover. This recommendation was further supported by literature research (Rogers et al. 2020 **Appendix T**; Weil 2020 **Appendix R**). Studies examining statistically robust designs have recommended sampling 100 points on a 20m transect using 5-10 randomly positioned replicates within a homogenous area (Nadon and Stirling 2006). Additionally, the experts recommended expanding substrate categorized as “bare substrate” to designate as hard bottom devoid of life, coarse sand, or fine sediment.

Photos and Videos at Survey Sites. The benthic experts suggested that photographs and videos should be methodically taken at all sites to provide interpretive visual data during expert reviews. Visual media could allow interpretation for reconciling discrepancies perceived in the data to refine BCG ratings or to confirm the outcome of BCG model application. The experts recommended the use of existing videographic methodology in the literature to assess transects and take photos of both common and unusual features at survey sites.

Transferability Goal or Assumption. The transferability of the benthic BCG numeric model should be demonstrated for other areas. The fish model has been proven to be transferable to the Florida Keys. The benthic experts could use the same sites of the NCRMP study in the Florida Keys that were used in the fish model testing, which could be completed with additional commitment and minor effort.

A basic premise of a BCG for any ecosystem is that it can be applied for any site within the bounds of model calibration. Model transferability has been demonstrated for freshwater BCGs by adapting the models to different regions where the ecological structure and function are similar to the original model. The BCG can also be adapted to different regions where the species presence and abundance are similar to sites surveyed in Puerto Rico, USVI, and south Florida. In some cases, the species included in model metrics might be substituted with other species performing those same roles in a different region. Several habitat types from the Western Atlantic that contain major architectural structure from calcite coral skeletons are based on *A. palmata* monocultures dominating reef crest environments. In other areas, *A. cervicornis* monocultures dominate back reef lagoonal areas and *Orbicella* spp. dominate deeper forereef areas (Weil 2020).

BCG Attribute I-V assignments for Hard Corals. Responses of coral populations and assemblages to increasing stress do not appear to be incremental or necessarily follow a predictable sequence of changes reflected by species turnover as documented in freshwater streams (US EPA 2012; Rogers et al. 2020). With increasing anthropogenic disturbance, coral species are unlikely to be replaced by more resilient species with the same functional roles, as observed in higher quality freshwater systems where sensitive taxa are replaced in lower quality streams by more tolerant taxa (Rogers et al. 2020; Weil 2020). The experts agreed more sustained research is required to understand the responses of different coral species more fully to the same stressors, and the response of the same coral species to different stressors.

Organism Condition. During several discussions among experts, coral condition was discussed as a possible indicator that might be tested for use as a metric in model rules. This could result in model rules pertaining to condition of organisms (colony mortality, bleaching, and disease) that would improve interpretations of reef conditions. (**Appendices R and T**). Rogers et al. (2020) suggested guidelines to begin discussions for ascertaining the health of reef corals. She proposed disease prevalence intervals for diseased corals affected by any tissue loss diseases as: BCG Level 1 (0–1 percent); BCG Level 2 (> 1–5 percent); BCG Level 3 (>5–10 percent); BCG Level 4 (>10–20 percent); BCG Level 5 (>20–30 percent); and BCG Level 6 (>30 percent).

Size Structure Demographics of coral populations. Experts suggested the size and demographic structure of the coral assemblage could be useful in determining overall condition of coral reefs. Rogers et al. (2020, **Appendix T**) presented evidence for how unfavorable or degraded habitat is reflected in specific patterns for unbalanced size structures of hard coral communities and potential long-term environmental consequences (Appendix T). For example, coral populations that are dominated by larger colonies at degraded sites might be attributed to lack of recruitment and (or) low survival of small colonies (McClanahan et. al. 2008). This is an area for continued research to better understand healthy size distributions and recruitment for each species, and to set expectations for biological condition.

References Cited

33 USC 1251 et seq. 1972. *Federal Water Pollution Control Amendments of 1972*.

50 CFR Part 223. 2014. Endangered and Threatened Wildlife and Plants: Final Listing Determinations on Proposal to List 66 Reef-Building Coral Species and to Reclassify Elkhorn and Staghorn Corals; Final Rule**.** *Federal Register* **79(175):** 53852-54123.

71 FR 26852–2686. 2006. *Endangered and Threatened Species: Final Listing Determinations for Elkhorn Coral and Staghorn Coral*. National Marine Fisheries Service (NMFS), National Oceanic and Atmospheric Administration (NOAA), Commerce. pp. 26852-26861.

79 FR 53851. 2014. *Endangered and Threatened Wildlife and Plants: Final Listing Determinations on Proposal to List 66 Reef-Building Coral Species and to Reclassify Elkhorn and Staghorn Corals***.** National Marine Fisheries Service (NMFS), National Oceanic and Atmospheric Administration (NOAA), Commerce. pp. 53851-54123.

Acevedo R and Morelock J. 1988. Effects of terrigenous sediment influx on coral reef zonation in southwestern Puerto Rico. *Proceedings of the 6th International Coral Reef Symposium* **2:**189–194.

Adams AJ, Dahlgren CP, Kellison GT, Kendall MS, Layman CA, Ley JA, Nagelkerken I, and Serafy JE. 2006. Nursery function of tropical back-reef systems. *Marine Ecology Progress Series* **318**:287–301.

Adams SM. 1990. Status and use of biological indicators for evaluating the effects of stress on fish. United States: *American Fisheries Society Symposium Series* **8:**1–191.

Adey W. 1978. Coral reef morphogenesis: a multidimensional model. *Science* **202**:831–837.

Adey WH, Macintyre IG, Stuckenrath R and Dill RF. 1977. Relic barrier reef system off St. Croix: Its implications with respect to the late Cenozoic coral reef development in the western Atlantic. *Proceedings of the Third International Coral Reef Symposium* **2:**15–23.

Aguilar-Perera A and Aguilar-Dávila W. 1996. A spawning aggregation of Nassau grouper *Epinephelus striatus* (Pisces: Serranidae) in the Mexican Caribbean. *Environmental Biology of Fishes.* **45(4):**351–61.

Aguilar-Perera A and Appeldoorn RS. 2007. Variation in juvenile fish density along the mangrove-seagrass-coral reef continuum in SW Puerto Rico. *Marine Ecology Progress Series* **348**:139–148.

Aguilar-Perera A and Appeldoorn RS. 2008. Spatial distribution of marine fishes along a cross-shelf gradient containing a continuum of mangrove-seagrass-coral reefs off Southwestern Puerto Rico. *Estuaries and Coastal Shelf Science* **76:**378–394.

Aguilar-Perera A, Schärer M and Nemeth M. 2006. Occurrence of juvenile Nassau grouper, *Epinephelus striatus* (Teleostei: Serranidae), off Mona Island, Puerto Rico: considerations of recruitment potential. *Caribbean Journal of Science* **42**:264–267.

Aguilar-Perera JA. 2004. *Coastal habitat connectivity of reef fishes from southwestern Puerto Rico*. PhD Thesis, University of Puerto Rico, Mayagüez, Puerto Rico.

Almy CC and Carrión Torres C. 1963. Shallow-water stony corals of Puerto Rico. *Caribbean Journal of Science* **3:**133–162.

Alvarado-Chacon, E., and Acosta, A., 2009, Population size-structure of the reef-coral *Montastraea annularis* in two contrasting reefs of a marine protected area in the southern Caribbean Sea. *Bulletin of Marine Science* **85(1)**:61–76.

Altizer S, Ostfeld RS, Johnson PT, Kutz S and Harvell CD. 2013. Climate change and infectious diseases: from evidence to a predictive framework. *Science.* **341(6145):**514–519.

Alvarado-Chacón EM and Acosta A. 2009. Population size-structure of the reef-coral *Montastraea annularis* in two contrasting reefs of a marine protected area in the southern Caribbean Sea. *Bulletin of Marine Science.* **85(1):**61–76.

Alvarez-Filip L, Carricart-Ganivet JP, Horta-Puga G and Iglesias-Prieto R. 2013. Shifts in coral-assemblage composition do not ensure persistence of reef functionality. *Scientific reports.* **3:**3486.

Alvarez-Filip L, Dulvy NK, Côté IM, Watkinson AR and Gill JA. 2011. Coral identity underpins architectural complexity on Caribbean reefs. *Ecological Applications.* **21(6):**2223–2231.

Alvarez-Filip L, Dulvy NK, Gill JA, Côté IM and Watkinson AR. 2009. Flattening of Caribbean coral reefs: region-wide declines in architectural complexity. *Proceedings of the Royal Society B-Biological Sciences* **276:** 3019–3025.

Amesbury SS. 1981. Effects of turbidity on shallow water reef fish assemblages in Truk, Eastern Caroline Islands. *Proceedings of the 4th International Coral Reef Congress* **6:** 491496.

Anderson CNK, Hsieh CH, Sandin SA, Hewitt R, Hallowed A, Beddington J, May RM and Sugihara G. 2008. Why fishing magnifies fluctuations in fish abundance. *Nature* **452**: 835–839.

Andradi-Brown DA, Gress E, Wright G, Exton DA, Rogers AD. 2016. Reef Fish Community Biomass and Trophic Structure Changes across Shallow to Upper-Mesophotic Reefs in the Mesoamerican Barrier Reef, Caribbean. *PLoS ONE* **11(6):** e0156641. doi:10.1371/journal.pone.0156641.

Anthony KR, Hoogenboom MO, Maynard JA, Grottoli AG and Middlebrook R. 2009. Energetics approach to predicting mortality risk from environmental stress: a case study of coral bleaching. *Functional ecology.* **23(3):**539–50.

Anthony KR, Kline DI, Diaz-Pulido G, Dove S and Hoegh-Guldberg O. 2008. Ocean acidification causes bleaching and productivity loss in coral reef builders. *Proceedings of the National Academy of Sciences.* **105(45):**17442–17446.

Antonious A. 1973. New observations in coral destruction in reefs. Association of Marine Laboratories of the Caribbean. **10:**3.

Appeldoorn RS and Lindeman KC. 2003. A Caribbean wide survey of marine reserves: spatial coverage and attributes of effectiveness. *Gulf and Caribbean Research* **14(2)**:139–154.

Appeldoorn RS and Meyers S. 1993. Puerto Rico and Hispaniola. In: Marine fishery resources of the Antilles. *FAO Fisheries Technical Paper* **326:** 99–158.

Appeldoorn RS, Friedlander A, Sladek Nowlis J, Ussegilo P and Mitchell-Chui A. 2003. Habitat connectivity on the insular platform of Old Providence-Santa Catalina, Colombia: mechanisms, limits and ecological consequences relevant to marine reserve design. *Gulf and Caribbean Research* **14**: 61–77.

Appeldoorn RS, Recksiek CW, Hill RL, Pagan FE and Dennis GD. 1997. Marine protected areas and reef fish movements: the role of habitat in controlling ontogenetic migration. *Proceedings of the 8th International Coral Reef Symposium* **2:** 1917–1922.

Appeldoorn RS. 2011. Can we stop the madness? Managing for resilience in coral reef fisheries. *Proceedings of the Gulf and Caribbean Fisheries Institute* **63**: 6–9.

Aronson RB and Precht WF. 2001a. White-band disease and the changing face of Caribbean coral reefs. *Hydrobiologia* **460:** 25–38.

Aronson RB and Precht WF. 2001b. Evolutionary paleoecology of Caribbean coral reefs. *Evolutionary paleoecology: the ecological context of macroevolutionary change*, pp.171–233.

Atkins JP, Burdon D, Elliott M. 2015. Identification of a practicable set of ecosystem indicators for coastal and marine ecosystem services. In: *Coastal Zones Ecosystem Services*. Springer, Cham. pp. 79–102.

Ault JS, Bohnsack JA and Meester GA. 1998. A retrospective (1979-1996) multispecies assessment of coral reef fish stocks in the Florida Keys. *Fishery Bulletin* **96(3):** 395–414.

Ault JS, Smith SG and Bohnsack JA. 2005. Evaluation of average length as an estimator of exploitation status for the Florida coral reef fish community. *Journal of Marine Science* **62**: 417–423.

Ault JS, Smith SG, Bohnsack JA, Luo J, Harper DE and McClellan DB. 2006. Building sustainable fisheries in Florida's coral reef ecosystem: positive signs in the Dry Tortugas. *Bulletin of Marine Science* **78:** 633–654.

Ault JS, Smith SG, Bohnsack JA, Luo J, Zurcher N, McClellan DB, Zeigler TA, Hallac DE, Patterson M, Feeley MW, Ruttenberg BI, Hunt J, Kimball D and Causey B. 2013. Assessing coral reef fish population and community changes in response to marine reserves in the Dry Tortugas, Florida, USA. *Fisheries Research* **144**: 28–37.

Ault JS, Smith SG, Browder JA, Nuttle W, Franklin EC, Luo J, DiNardo GT, and Bohnsack JA. 2014. Indicators for assessing the ecological dynamics and sustainability of southern Florida's coral reef and coastal fisheries. *Ecological Indicators* **44**:164–72.

Ault JS, Smith SG, Luo J, Monaco ME and Appeldoorn RS. 2008. Length-Based Assessment of Sustainability Benchmarks for Coral Reef Fishes in Puerto Rico. *Environmental Conservation* **35**: 221–231.

Ault TR and Johnson CR. 1998. Spatial variation in fish species richness on coral reefs: habitat fragmentation and stochastic structuring processes. *Oikos.* **1:**354–364.

Baird AH, Birrell CL, Hughes TP, McDonald A, Nojima S, Page CA, Prachett MS and Yamasaki H. 2009a. Latitudinal variation in reproductive synchrony in Acropora assemblages: Japan vs. Australia. *Galaxea, Journal of Coral Reef Studies.* **11(2):**101–8.

Baird AH, Guest JR and Willis BL. 2009b. Systematic and biogeographical patterns in the reproductive biology of scleractinian corals. *Annual Review of Ecology, Evolution, and Systematics.* **40:**551–71.

Bak RP 1983. Neoplasia, regeneration and growth in the reef-building coral Acropora palmata. *Marine Biology.* **77(3):**221–227.

Bak RP and Meesters EH. 1998. Coral population structure: the hidden information of colony size-frequency distributions. *Marine Ecology Progress Series.* **162:**301–306.

Bak RP and Meesters EH. 1999. Population structure as a response of coral communities to global change. *American Zoologist* **39(1):** 56–65.

Bak RPM and Elgershuizen JHBW. 1976. Patterns of oil-sediment rejection in corals. *Marine Biology* **37:** 105–113.

Bak RPM and Steward-Van Es Y. 1980. Regeneration of superficial damage in the scleractinian corals *Agaricia agaricites, f. purpurae* and *Porites astreoides*. *Bulletin of Marine Science* **30:** 883–887.

Bak RPM. 1978. Lethal and sublethal effects of dredging on reef corals. *Marine Pollution Bulletin* **9:** 4–16.

Bak RPM. 1983. Aspects of community organization in Caribbean stony corals (Scleractinia). In: Coral reefs, seagrass beds and mangroves: their interaction in the coastal zones of the Caribbean (eds.) J.C. Ogden and E.H. Gladfelter. *UNESCO Report on Marine Science* **23:** 51–68.

Bak RP and Meesters EH. 1998. Coral population structure—The hidden information of colony size-frequency distributions. *Marine Ecology Progress Series* **162:** 301–306.

Baker AC and Cunning R. 2015. Coral "bleaching" as a generalized stress response to environmental disturbance. *Diseases of Coral* **2:**396–409.

Baker AC, Glynn PW and Riegl B. 2008. Climate change and coral reef bleaching: An ecological assessment of long-term impacts, recovery trends and future outlook. *Estuarine and Coastal Shelf Science* **80:** 435–471.

Baker AC, Starger CJ, McClanahan TR and Glynn PW. 2004. Corals' adaptive response to climate change. *Nature.* **430(7001):**741

Baker AC. 2001. Reef corals bleach to survive change. *Nature.* **411(6839):**765–766.

Baker AC. 2003. Flexibility and specificity in coral-algal symbiosis: diversity, ecology, and biogeography of Symbiodinium. *Annual Review of Ecology, Evolution, and Systematics.* **34(1):** 661–689.

Baker AC. 2004. Symbiont diversity on coral reefs and its relationship to bleaching resistance and resilience. *In: Coral health and disease.* Springer, Berlin, Heidelberg. pp. 177–194.

Baker EK, Puglise KA and Harris PT (Eds.). 2016. *Mesophotic coral ecosystems — A lifeboat for coral reefs?* The United Nations Environment Programme and GRID-Arendal, Nairobi and Arendal, 98 pp.

Ballantine DL, Appeldoorn RS, Yoshioka P, Weil E, Armstrong R, Garcia JR, Otero E, Pagan F, Sherman C, Hernandez-Delgado EA, Bruckner A and Lilyestrom C. 2008. Biology and Ecology of Puerto Rican Coral Reefs. In: *Coral Reefs of the USA. Coral Reefs of the World, (eds.) Riegl B.M., Dodge R.E. vol 1*. Springer, Dordrecht. doi:10.1007/9781-4020-6847-8_9.

Barley SC, Clark TD and Meeuwig JJ. 2020. Ecological redundancy between coral reef sharks and predatory teleosts. *Reviews in Fish Biology and Fisheries* **30**: 153–172.

Barnes DJ. 1970. Coral skeletons: an explanation of their growth and structure. *Science* **170(3964)**:1305–1308.

Barrett SC. 1998. The evolution of mating strategies in flowering plants. *Trends in Plant Science.* **3(9):**335–341.

Bastidas C, Bone D, Cróquer A, Debrot D, Garcia E, Humanes A, Ramos R and Rodríguez S. 2012. Massive hard coral loss after a severe bleaching event in 2010 at Los Roques, Venezuela. *Revista de Biología Tropical.* **60:**29–37.

Beck MW, Heck KL, Able KW, Childers DL, Eggleston DB, Gillanders BM, Halpern B, Hays CG, Hoshino K, Minello TJ and Orth RJ. 2001. The identification, conservation, and management of estuarine and marine nurseries for fish and invertebrates: a better understanding of the habitats that serve as nurseries for marine species and the factors that create site-specific variability in nursery quality will improve conservation and management of these areas. *Bioscience.* **51(8):**633–641.

Beets J and Friedlander A. 1998. Evaluation of a conservation strategy: a spawning aggregation closure for red hind, *Epinephelus guttatus*, in the U.S. Virgin Islands. *Environmental Biology of Fishes* **55:** 91–98.

Beets J and Friedlander AL. 1992. Stock analysis and management strategies for Red Hind, *Epinephelus guttatus* in the US Virgin Islands. *Proceedings of the Gulf and Caribbean Fisheries Institute.* ***42:*** 66–80.

Beets J, Lewand L and Zullo E. 1986. *Marine community descriptions and maps of bays within the Virgin Islands National Park/Biosphere Reserve*. Biosphere Reserve Research Report no. 2 VIRMC/NPS, 118 pp.

Beets J. 1997. Effects of a predatory fish on the recruitment and abundance of Caribbean coral reef fishes. *Marine Ecology Progress Series.* **148:**11–21.

Bejarano I and Appeldoorn RS. 2013. Seawater turbidity and fish communities on coral reefs of Puerto Rico. *Marine Ecology Progress Series* **474**: 217–226.

Bejarano I, Appeldoorn RS and Nemeth M. 2014. Fishes associated with mesophotic coral ecosystems in La Parguera, Puerto Rico. *Coral Reefs.* **33(2):**313–328.

Bejarano-Rodríguez I. 2006. *Relationships Between Reef Fish Communities, Water and Habitat Quality on Coral Reef*s. Master's Thesis in Marine Sciences, University of Puerto Rico, Mayagüez, PR.

Bell JD and Galzin R. 1984. Influence of live coral cover on coral-reef fish communities. *Marine Ecology Progress Series.* **15(3):**265–274.

Bell JD and Galzin R. 1988. Distribution of coral and fish in the lagoon at Mataiva: Potential for increase through mining? *Proceedings of the 8th International Coral Reef Symposium*. **2:** 347–352.

Bellwood DR, Hughes TP, Folke C and Nyström M. 2004. Confronting the coral reef crisis. *Nature* **429:** 827–833.

Beukers JS and Jones GP. 1997. Habitat complexity modifies the impact of piscivorous on a coral reef fish population. *Oecologia* **114:** 50–59.

Beverton RJ and Holt SJ. 1959. A review of the lifespans and mortality rates of fish in nature, and their relation to growth and other physiological characteristics. *In: CIBA Foundation colloquia on ageing*. **5**:142–180.

Bohnsack JA and Bannerot SP. 1986. *A stationary visual census technique for quantitatively assessing community structure of coral reef fishes*. NOAA Technical Report NMFS 41.

Bohnsack JA and Harper DE. 1988. *Length-weight relationships of selected marine reef fishes from the southeastern United States and the Caribbean*. Technical memorandum 215. National Oceanic and Atmospheric Administration, National Marine Fisheries Service, Miami, Florida.

Bonfil, R. 1996. *Pattern and trends in world shark fisheries* (abstract). Proceeding from the sharks and man workshop of the second world fisheries congress, Brisbane, Australia: 5 N.A. Gribble., G. McPherson, & B. Lane (ed.) Department of Primary Industries Queensland. QC98001

Borer ET, Seabloom EW, Shurin JB, Anderson KE, Blanchette CA, Broitman B, Cooper SD and Halpern BS. 2005. What determines the strength of a trophic cascade? *Ecology.* **86(2):**528–37.

Boström C, Pittman SJ, Simenstad C and Kneib RT. 2011. Seascape ecology of coastal biogenic habitats: advances, gaps, and challenges. *Marine Ecology Progress Series.* **427:**191–217.

Bouchon-Navaro Y and Bouchon C. 1989. Correlations between chaetodontid fishes and coral communities of the Gulf of Aqaba (Red Sea). *Environmental Biology of Fishes.* **25(1-3):**47–60.

Bourne D, Iida Y, Uthicke S, and Smith-Keune C. 2008. Changes in coral-associated microbial communities during a bleaching event. *The ISME Journal* **2**:350–363.

Bradley P and Santavy DL. 2016. Caribbean coral reefs—Benchmarking a Biological Condition Gradient for Puerto Rican coral reefs, In: *Appendices to A practitioner's guide to the Biological Condition Gradient—A framework to describe incremental change in aquatic ecosystems*. U.S. Environmental Protection Agency EPA 842-R-16-001, p. B53–B76.

Bradley P, Campbell DE, Fisher WS, Lehrter JC, Principe P, Sanchirico JN, Yee SH. unpublished. *Ecosystem Studies: Coral Reef Research Implementation Plan.* Internal unpublished document. US EPA Office of Research and Development, Gulf Breeze, FL**.** 107 pp.

Bradley P, Fisher W and Fore L. 2014a. *Coral Reef Monitoring Needs Assessment Workshop, St. Croix, U.S. Virgin Islands, September 11-13, 2007*. U.S. Environmental Protection Agency, Office of Research and Development, Narragansett, RI. EPA/600/R-14/368.

Bradley P, Fore L, Fisher W and Davis W. 2010. *Coral Reef Biological Criteria: Using the Clean Water Act to Protect a National Treasure*. U.S. EPA, ORD, AED, Narragansett, RI. EPA/600/R-10/054.

Bradley P, Jessup B, Gerritsen J and Gallindo A. 2016. *The Coral Reef Biological Condition Gradient: Moving Toward Quantitative Criteria from Species-Based Attributes*. Tetra Tech, Inc. Prepared for the U.S. Environmental Protection Agency, Office of Water, Office of Science and Technology, Washington, D.C.

Bradley P, Jessup B, Pittman SJ, Jeffrey CFJ, Ault JS, Carrubba L, Lilyestrom C, Appeldoorn R, Schärer MT, Walker BK, McField M, Santavy DL, Smith T, García-Moliner G, Smith SG, Huertas E, Gerritsen J, Oliver LM, Horstmann CL, Jackson SK. 2020. Development of a reef fish biological condition gradient model with quantitative decision rules for the protection and restoration of coral reef ecosystems. *Marine Pollution Bulletin* **159**: 111387

Bradley P, Santavy DL and Gerritsen J. 2014b. Workshop on Biological Integrity of Coral Reefs. *In: Proceedings of a workshop on biological integrity of coral reefs, Caribbean Coral Reef Institute, Isla Magueyes, La Parguera, Puerto Rico, August 21–22, 2012*. Narragansett, R.I., U.S. Environmental Protection Agency, Office of Research and Development, Atlantic Ecology Division, EPA/600/R-13/350.

Bright AJ, Rogers C, Brandt M, Muller E and Smith T. 2016. Disease prevalence and snail predation associated with swell-generated damage on the threatened coral, *Acropora palmata* (Lamarck). *Frontiers in Marine Science*: **3:**77-80.

Brokovich E, Ben-Ari T, Kark S, Kiflawi M, Dishon G, Iluz D and Shashar N. 2010. Functional changes of the visual system of the damselfish *Dascyllus marginatus* along its bathymetric range. *Physiology & behavior* **101(4):**413–421.

Brokovich E, Einbinder S, Shashar N, Kiflawi M and Kark S. 2008. Descending to the twilight-zone: changes in coral reef fish assemblages along a depth gradient down to 65 m. *Marine Ecology Progress Series* **371:** 253–262.

Brown BE, LeTissier MDA, Scoffin TP and Tudhope AW. 1990. Evaluation of the environmental impact of dredging on intertidal coral reefs at Ko Phuket, Thailand, using ecological and physiological parameters. *Marine Ecology Progress Series* **65:** 273–281.

Brown BE. 1997. Coral bleaching: causes and consequences. *Coral Reefs* **16:** S129—S138.

Brown CJ, Jupiter SD, Lin HY, Albert S, Klein C, Maina JM, Tulloch VJ, Wenger AS and Mumby PJ. 2017. Habitat change mediates the response of coral reef fish populations to terrestrial run-off. *Marine Ecology Progress Series* **576**: 55–68.

Brown MT and Vivas MB. 2005 Landscape development intensity index. *Environmental Monitoring and Assessment* **101:** 289–309.

Browne NK, Tay J and Todd PA. 2015. Recreating pulsed turbidity events to determine coral–sediment thresholds for active management. *Journal of experimental marine biology and ecology.* **466:**98–109.

Bruckner AW and Bruckner RJ. 1997a. Outbreak of coral disease in Puerto Rico. *Coral Reefs* **16**: 260.

Bruckner AW and Bruckner RJ. 1997b. The persistence of black- band disease in Jamaica: impact on community structure. *Proceedings of the 8th International Coral Reef Symposium* **1:** 601–606.

Bruckner AW and Bruckner RJ. 2003. Condition of coral reefs off less developed coastlines of Curaçao (stony corals and algae). *Atoll Research Bulletin* **496:** 370–393.

Bruckner AW and Bruckner RJ. 2006. Consequences of yellow-band disease (YBD) on *Montastraea annularis* (species complex) populations on remote reefs off Mona Island, Puerto Rico. *Diseases of Aquatic Organisms* **69:** 67–73.

Bruckner AW and Hill R. 2009. Ten years of change to coral communities off Mona and Desecheo Islands, Puerto Rico, from disease and bleaching. *Diseases of Aquatic Organisms* **87:** 19–31.

Bruckner, AW. 2012. Factors contributing to the regional decline of *Montastraea annularis* (complex). In: *Proceedings of the 12th International Coral Reef Symposium*, Cairns, Australia, pp. 9-13.

Bruno JF and Selig ER. 2007. Regional decline of coral cover in the Indo-Pacific: timing, extent, and subregional comparisons. *PLoS One* **2**: 711.

Bruno JF, Sweatman H, Precht WF, Selig E and Schutte VCW. 2009. Assessing evidence of phase shifts from coral to macroalgal dominance on coral reefs. *Ecology* **90(6):** 1478–1484.

Brylske A. 2006. Encyclopedia of Recreational Diving, 3rd edition. United States PADI. ISBN 1-878663-01-1.

Buddemeier RW and Fautin DG. 1993. Coral bleaching as an adaptive mechanism. *Bioscience.* **43(5):**320–326.

Buddemeier RW and Kinzie RA. 1976. Coral growth. *Oceanography Marine Biology Annual Review* **14:**183–225.

Buddemeier RW, Baker AC, Fautin DG and Jacobs JR. 2004. The adaptive hypothesis of bleaching. *Coral Health and Disease* (eds.) Rosenberg E Loya Y, . Springer-Verlag, Berlin. pp. 427 – 444.

Bullock LH, Murphy MD, Godcharles MF and Mitchell ME. 1992. Age, growth, and reproduction of jewfish *Epinephelus itajara* in the eastern Gulf of Mexico. *Fishery Bulletin.* (**2**).

Burge CA, Eakin CM, Friedman CS, Froelich B, Hershberger PK, Hofmann EE, Petes LE, Prager KC, Weil E, Willis BL and Ford SE. 2014. Climate change influences on marine infectious diseases: implications for management and society. *Annual Review of Marine Science*. **6**:249–277.

Burge CA, Kim CJS, Lyles JM and Harvell CD. 2013. Special issue oceans and human health—The ecology of marine opportunists. *Microbial Ecology* **65:** 869–879.

Burton ML, Brennan KJ, Muñoz RC and Parker Jr R. 2005. Preliminary evidence of increased spawning aggregations of mutton snapper (*Lutjanus analis*) at Riley's Hump two years after establishment of the Tortugas South Ecological Reserve. *Fishery Bulletin.* **103(2):**404–10.

Bythell JC, Gladfelter EH and Bythell M. 1993. Chronic and catastrophic natural mortality of three common Caribbean reef corals. *Coral Reefs* **12:** 143–152.

Cairns J, Jr. 1977. Quantification of biological integrity, In: Ballentine RK and Guarria LJ. (eds). *The integrity of water—Proceedings of a symposium*. Washington, D.C., U.S. Environmental Protection Agency p. 171–187.

Cairns SD. 2007. Deep-water corals: an overview with special reference to diversity and distribution of deep-water scleractinian corals. *Bulletin of marine Science.* **81(3):**311–22.

Caldow C, Clark R, Edwards K, Hile SD, Menza C, Hickerson E, and Schmahl GP. 2009. Biogeographic Characterization of Fish Communities and Associated Benthic Habitats within the Flower Garden Banks National Marine Sanctuary: Sampling Design and Implementation of SCUBA Surveys on the Coral Caps. NOAA Technical Memorandum NOS NCCOS 81. Silver Spring, MD. 134 pp.

Calnan JM, Smith TB, Nemeth RS, Kadison E, Blondeau J. 2008. Coral disease prevalence and host susceptibility on mid-depth and deep reefs in the United States Virgin Islands. *Revista de Biologia Tropical*.

Carpenter KE, Abrar M, Aeby G, Aronson RB, Banks S, Bruckner A, Chiriboga A, Cortes J, Delbeek JC, DeVantier L, Edgar GJ, Edwards AJ, Fenner D, Guzman HM, Hoeksema BW, Hodgson G, Johan O, Licuanan WY, Livingstone SR, Lovell ER, Moore JA, Obura DO, Ochavillo D, Polidoro BA, Precht WF, Quibilan MC, Reboton C, Richards ZT, Rogers AD, Sanciangco J, Sheppard A, Sheppard C, Smith J, Stuart S, Turak E, Veron JEN, Wallace C, Weil E and Wood E. 2008. One-third of reef-building corals face elevated extinction risk from climate change and local impacts. *Science* **321**: 560–563.

Carpenter KE, Miclat RI, Albaladejo VD and Corpuz VT. 1981. The influence of substrate structure on the abundance and diversity of Philippine reef fishes. *Proceedings of the Fourth International Coral Reef Symposium* **2**: 497–502.

Carter J and Perrine D. 1994. A spawning aggregation of dog snapper, *Lutjanus jocu* (Pisces: Lutjanidae) in Belize, Central America. *Bulletin of Marine Science.* **55(1):**228–34.

Castella E and Speight MCD. 1996. Knowledge representation using fuzzy coded variables: an example based on the use of *Syrphidae* (Insecta, Diptera) in the assessment of riverine wetlands. *Ecological Modelling* **85**: 13–25.

Catanzaro D, Nemeth R, Rogers C, Hillis-Starr Z and Taylor M. 2002. The status of the coral reefs of the US Virgin Islands. *The State of Coral Reef Ecosystems of the United States and Pacific Freely Associated States*. National Oceanic and Atmospheric Administration, Silver Spring, MD, 2002 pp. 131–142.

Cerveny K, Appeldoorn RS, and Recksiek CW. 2011. Managing habitat in coral reef ecosystems for fisheries: just what is essential? *Proceedings of the Gulf and Caribbean Fisheries Institute.* **63**:23–36.

Cerveny K. 2006. Distribution patterns of reef fishes in southwest Puerto Rico, relative to structural habitat, cross—shelf location, and ontogenetic stage. Master's Thesis, University of Puerto Rico - Mayagüez.

Chabanet P, Dufour V, and Galzin R. 1995. Disturbance impact on reef fish communities in Reunion Island (Indian Ocean). *Journal of Experimental Marine Biology and Ecology* **188**:29–48.

Chalker BE and Barnes DJ. 1990. Gamma densitometry for the measurement of skeletal density. *Coral Reefs* **9(1):**11–23.

Chansang H, Boonyanate P and Charuchinda M. 1981.Effect of sedimentation from coastal mining on coral reefs on the northwestern coast of Phuket Island. Thailand. *Proceedings of the 4th International Coral Reef. Symposium* **1:** 129–136.

Chornesky EA and Peters EC. 1987. Sexual reproduction and colony growth in the scleractinian coral Porites astreoides. *The Biological Bulletin.* **172(2):**161–177.

Chou LM. 1997. The status of southeast Asian coral reefs. *Proceedings of the 8th International Coral Reef Symposium* **1:** 317–322.

Christensen JD, Jeffrey CFG, Caldow C, Monaco ME, Kendall MS and Appeldoorn RS. 2003. Cross-Shelf Habitat Utilization Patterns of reef fishes in southwestern Puerto Rico. *Gulf and Caribbean Research* **14**: 9–27.

Christensen V and Pauly D. 1997. Placing fisheries resources in their ecosystem context. *EC Fisheries Cooperative Bulletin.* **10:**9–14.

Cicchetti G and Greening H. 2011. Estuarine biotope mosaics and habitat management goals: an application in Tampa Bay, FL, USA. *Estuaries and Coasts.* **34(6):**1278–1292.

Claro R and García-Arteaga JP. 1994. Estructura de las comunidades de peces en los arrecifes del grupo insular Sabana-Camagüey, Cuba. *Avicennia.* **2:**83–107.

Claro R and Lindeman KC. 2003. Spawning Aggregation Sites of Snapper and Grouper Species (Lutjanidae and Serranidae) on the Insular Shelf of Cuba. *Gulf and Caribbean Research* **14**: 91–106.

Claudet J, Osenberg CW, Domenici P, Badalamenti F, Milazzo M, Falcón JM, Bertocci I, Benedetti-Cecchi L, García-Charton JA, Goñi R and Borg JA. 2010. Marine reserves: fish life history and ecological traits matter. *Ecological applications.* **20(3):**830–839.

Claydon J. 2004. Spawning aggregations of coral reef fishes: characteristics, hypotheses, threats and management. *Oceanography and Marine Biology: An Annual Review.* **42**:265–302.

Cocheret de la Morinière E, Pollus BJA, Nagelkerken I and van der Velde G. 2002a. Post-settlement Life Cycle Migration Patterns and Habitat Preference of Coral Reef Fish that use Seagrass and Mangrove Habitats as Nurseries. *Estuarine, Coastal and Shelf Science* **55**: 309–321.

Cole AJ, Pratchett MS and Jones GP. 2008. Diversity and functional importance of coral-feeding fishes on tropical coral reefs. *Fish and Fisheries.* **9(3):**286–307.

Coleman FC, Koenig CC, Huntsman GR, Musick JA, Eklund AM, McGovern JC, Chapman RW, Sedberry GR and Grimes CB. 2000. Long-lived Reef Fishes. *Fisheries.* **10:**15.

Coles SL, Jokiel PL and Lewis CR. 1976. Thermal tolerance in tropical versus subtropical Pacific reef corals. *Pacific Science* **30:** 159–166.

Colin PL, Shapiro DY, Weiler D. 1987. Aspects of the reproduction of two groupers, *Epinephelus guttatus* and *E. striatus* in the West Indies. *Bulletin of Marine Science*. **40(2)**:220–230.

Colin PL. 1974. Observation and collection of deep-reef fishes off the coasts of Jamaica and British Honduras (Belize). *Marine Biology.* **24(1):**29–38.

Colin PL. 1976. Filter Feeding and Predation on the Eggs of *Thallasoma Sp*. by the Scombrid Fish *Rastrelliger kanagurta*. *Copeia* **1976**: 596–597.

Colvocoresses J, Acosta A. 2007. A large-scale field comparison of strip transect and stationary point count methods for conducting length-based underwater visual surveys of reef fish populations. *Fisheries Research.* **85(1-2)**:130–141.

Connor DW, Hiscock K, Foster-Smith RL and Covey R. 1997. A classification system for benthic marine biotopes. *Oceanographic Literature Review.* **2(44):**126.

Cortes JN and Risk MJ. 1985. A reef under siltation stress: Cahuita, Costa Rica. *Bulletin of Marine Science* **36:** 339–356.

Costa BM, Bauer LJ, Battista TA, Mueller PW and Monaco ME. 2009. *Moderate-Depth Benthic Habitats of St. John, U.S. Virgin Islands*. NOAA Technical Memorandum NOS NCCOS 105. Silver Spring, MD. P. 57.

Costa BM, Kendall MS, Edwards K, Kagesten G, Battista TA. 2013. *Benthic Habitats of Fish Bay, Coral Bay and the St. Thomas East End Reserve.* NOAA Technical Memorandum NOS NCCOS p. 175.

Costello MJ. 2009. Distinguishing marine habitat classification concepts for ecological data management. *Marine Ecology Progress Series.* **397:**253–268.

Courtney LA, Fisher WS, Raimondo S, Oliver LM and Davis WS. 2007. Estimating three-dimensional colony surface area of field corals. *Journal of Experimental Marine Biology and Ecology* **351**: 234–242.

Cróquer A and Weil E. 2009, Changes in Caribbean coral disease prevalence after the 2005 bleaching event. *Diseases of Aquatic Organisms* **87(1):** 33–43.

Cruz-Piñón G, Carricart-Ganivet JP and Espinoza-Avalos J. 2003. Monthly skeletal extension rates of the hermatypic corals *Montastraea annularis* and *Montastraea faveolata*: biological and environmental controls. *Marine Biology*. **143(3):**491–500.

Dahlgren CP and Eggleston DB. 2000. Ecological Processes Underlying Ontogenetic Habitat Shifts in a Coral Reef Fish. *Ecology* **81(8):** 2227–2240.

Dahlgren CP, Kellison T, Adams AJ, Gillanders BM, Kendall MS, Ley JA, Nagelkerken I and Serafy JE. 2006. Marine nurseries and effective juvenile habitats: concepts and applications. *Marine Ecology Progress Series* **312**: 291–295.

Dammann AE and Nellis DW. 1992. A natural history atlas to the cays of the US Virgin Islands. *Pineapple Press, Inc*. Sarasota, FL.

Darling ES, Alvarez-Filip L, Oliver TA, McClanahan TR, Côté IM. 2012. Evaluating life-history strategies of reef corals from species traits. *Ecology Letters.* **15(12):**1378–1386.

Davies CE and Moss D. 2004. EUNIS Habitat Classification. Marine habitat types: Revised classification and criteria, September 2004. *Centre for Ecology & Hydrology.* **84.**

Davies PE, Harris JH, Hillman TJ and Walker KF. 2010. The Sustainable Rivers Audit: assessing river ecosystem health in the Murray Darling Basin, Australia. *Marine and Freshwater Research* **61**: 764–777.

DeMartini EE, Friedlander AM, Sandin SA and Sala E. 2008. Differences in fish-assemblage structure between fished and unfished atolls in the northern Line Islands, central Pacific. *Marine Ecology Progress Series* **365**: 199–215.

Dennis GD. 1992. Island mangrove habitats as spawning and nursery areas for commercially important fishes in the Caribbean. *Gulf and Caribbean Fisheries Institute.* **41:**205–225.

DeSalvo MK, Voolstra CR, Sunagawa S, Schwarz JA, Stillman JH, Coffroth MA, Szmant AM and Medina M. 2008. Differential gene expression during thermal stress and bleaching in the Caribbean coral *Montastraea faveolata*. *Molecular Ecology* **17(17):** 3952–3971.

Desbiens AA, Roff G, Robbins WD, Taylor BM, Castro-Sanguino C, Dempsey A and Mumby P. 2021. Revisiting the paradigm of shark-driven trophic cascades in coral reef ecosystems. *Ecology* **102(4)**: e03303.

Devlin M and B Schaffelke. 2009. Spatial extent of riverine flood plumes and exposure of marine ecosystems in the Tully Coastal region, Great Barrier Reef. *Marine and Freshwater Research* **60**: 1109–1122.

Diaz-Pulido G, Harii S, McCook LJ and Hoegh-Guldberg O. 2010. The impact of benthic algae on the settlement of a reef-building coral. *Coral Reefs.* **29(1):**203–208.

Dikou A and van Woesik R. 2006. Survival under chronic stress from sediment load: Spatial patterns of hard coral communities in the southern islands of Singapore. *Marine Pollution Bulletin* **52:** 7–21.

Dodge RE and Brass GW. 1984. Skeletal extension, density and calcification of the reef coral, *Montastrea annularis*: St. Croix, U.S. Virgin Islands. *Bulletin of Marine Science* **34:** 288–307.

Dodge RE and Vaisnys JR. 1977. Coral populations and growth patterns: responses to sedimentation and turbidity associated with dredging. *Journal of Marine Research* **35:** 715–730.

Dodge RE, Aller RC and Thomson J. 1974. Coral growth related to resuspension of bottom sediments. *Nature.* **247(5442):**574–7.

Domeier ML and Colin PL. 1997. Tropical reef fish spawning aggregations: defined and reviewed. *Bulletin of Marine Science.* **60(3):**698–726.

Donner SD, Skirving WJ, Little CM, Oppenheimer M and Hoegh-Guldberg OV. 2005. Global assessment of coral bleaching and required rates of adaptation under climate change. *Global Change Biology.* **11(12):**2251–2265.

Dorenbosch M, Grol MG, Nagelkerken I and Van der Velde G. 2006. Seagrass beds and mangroves as potential nurseries for the threatened Indo-Pacific humphead wrasse, *Cheilinus undulatus* and Caribbean rainbow parrotfish, *Scarus guacamaia*. *Biological Conservation* **129(2):**277–282.

Dorenbosch M, Van Riel MC, Nagelkerken I and Van der Velde G. 2004. The relationship of reef fish densities to the proximity of mangrove and seagrass nurseries. *Estuarine, Coastal and Shelf Science.* **60(1):**37–48.

Dorenbosch M, Verberk WC, Nagelkerken I and Van der Velde G. 2007. Influence of habitat configuration on connectivity between fish assemblages of Caribbean seagrass beds, mangroves and coral reefs. *Marine Ecology Progress Series.* **334:**103–116.

Dorenbosch M, Verweij MC, Nagelkerken I, Jiddawi N and Van der Velde G. 2004. Homing and daytime tidal movements of juvenile snappers (Lutjanidae) between shallow-water nursery habitats in Zanzibar, western Indian Ocean. *Environmental Biology of Fishes.* **70(3):**203–209.

Dramstad W, Olson JD and Forman RT. 1996. *Landscape ecology principles in landscape architecture and land-use planning*. Harvard University Graduate School of Design, Island Press and the American Society of Landscape Architects.

Droesen WJ. 1996. Formalisation of ecohydrological expert knowledge applying fuzzy techniques. *Ecological Modeling* **85**:75–81.

Dryer S and Logan A. 1978. Holocene reefs and sediments of Castle Harbour, Bermuda. *Journal of Marine Research* **36**: 399–425.

Dugan JE and Davis GE. 1993. Applications of marine refugia to coastal fisheries management. *Canadian Journal of Fisheries and Aquatic Sciences*. **50(9):**2029–2042.

Dustan P, Doherty O and Pardede S. 2013. Digital reef rugosity estimates coral reef habitat complexity. *PLoS ONE* **8(2)**: e57386.

Eakin CM, Lough JM and Heron SF. 2009. Climate variability and change: monitoring data for increased coral bleaching stress. Ch 4 in: *Coral Bleaching Patterns, Processes, Causes and Consequences*, (eds.) Oppen MJH and Lough JM, Springer-Verlag Berlin Heidelberg p. 185.

Eakin CM, Morgan JA, Heron SF, Smith TB, Liu G, Alvarez-Filip L, Baca B, Bartels E, Bastidas C, Bouchon C, Brandt M, Bruckner AW, Bunkley-Williams L, Cameron A, Causey BD, Chiappone M, Christensen TRL, Crabbe MJC, Day O, de la Guardia E, Díaz-Pulido G, DiResta D, Gil-Agudelo DL, Gilliam DS, Ginsburg RN, Gore S, Guzmán HM, Hendee JC, Hernández-Delgado EA, Husain E, Jeffrey CFG, Jones RJ, Jordán-Dahlgren E, Kaufman LS, Kline DI, Kramer PA, Lang JC, Lirman D, Mallela J, Manfrino C, Maréchal J-P, Marks K, Mihaly J, Miller WJ, Mueller EM, Muller EM, Orozco Toro CA, Oxenford HA, Ponce-Taylor D, Quinn N, Ritchie KB, Rodríguez S, Ramírez AR, Romano S, Samhouri JF, Sánchez JA, Schmahl GP, Shank B V., Skirving WJ, Steiner SCC, Villamizar E, Walsh SM, Walter C, Weil E, Williams EH, Roberson KW and Yusuf Y. 2010. Caribbean Corals in Crisis: Record Thermal Stress, Bleaching, and Mortality in 2005. *PLoS ONE* 5:e13969. doi: 10.1371/journal.pone.0013969.

Eakin CM, Sweatman HPA, and Brainard RE. 2019. The 2014–2017 global-scale coral bleaching event—Insights and impacts. *Coral Reefs* **38**:539–545.

Edinger EN and Risk MJ. 1999. Coral morphology triangles indicate conservation value for coral reef assessment and management. *Biological Conservation.* **92:**1–3.

Edinger EN and Risk MJ. 2000. Reef classification by coral morphology predicts coral reef conservation value. *Biological Conservation.* **92(1):**1–3.

Edinger EN, Jompa J, Limmon GV, Widjatmoko W and Risk MJ. 1998. Reef degradation and coral biodiversity in Indonesia: Effects of land-based pollution, destructive fishing practices and changes over time. *Marine Pollution Bulletin* **36**: 617–630.

Edmunds PJ and Elahi R. 2007. The demographics of a 15-year decline in cover of the Caribbean reef coral *Montastraea annularis*. *Ecological Monographs.* **77(1):**3–18.

Edmunds PJ. 2002. Long-term dynamics of coral reefs in St. John, US Virgin Islands. *Coral Reefs.* **21(4):**357–367.

Edmunds PJ. 2005. Effect of elevated temperature on aerobic respiration of coral recruits. *Marine Biology.* **146(4):**655–663.

Eggleston DB. 1995. Recruitment in Nassau grouper *Epinephelus striatus*: post-settlement abundance, microhabitat features, and ontogenetic habitat shifts. *Marine Ecology Progress Series.* **124:**9–22.

Emery AR. 1973. Comparative ecology and functional osteology of fourteen species of damselfish (Pisces: Pomacentridae) at Alligator Reef, Florida Keys. *Bulletin of Marine Science.* **23(3):**649-770.

Ennis RS, Brandt ME, Wilson KR and Smith TB. 2016. Coral reef health response to chronic and acute changes in water quality in St. Thomas, United States Virgin Islands. *Marine Pollution Bulletin* **111**: 418-427.

Erftemeijer PL, Riegl B, Hoeksema BW and Todd PA. 2012. Environmental impacts of dredging and other sediment disturbances on corals—A review. *Marine Pollution Bulletin* **64(9):**1737–1765.

Estes JA, Terborgh J, Brashares JS, Power ME, Berger J, Bond WJ, Carpenter SR, Essington TE, Holt RD, Jackson JB and Marquis RJ. 2011. Trophic downgrading of planet Earth. *Science.* **333(6040):**301-306.

Evermann BW. 1900. General report on the investigations in Puerto Rico of the United States Fish Commission Steamer Fish Hawk in 1899. *Bulletin of the United States Fish Commission* **1:** 1–26.

Fabricius KE. 2005. Effects of terrestrial runoff on the ecology of corals and coral reefs: review and synthesis. *Marine Pollution Bulletin* **50:** 125–146.

Farina A and Napoletano B. 2010. Rethinking the landscape: new theoretical perspectives for a powerful agency. *Biosemiotics.* **3(2):**177–187.

Feary DA, Almany GR, McCormick MI and Jones GP. 2007. Habitat choice, recruitment and the response of coral reef fishes to coral degradation. *Oecologia.* **153(3):**727–737.

Federal Geographic Data Committee (FGDC). 2012. *Coastal and Marine Ecological Classification Standard.* **(**FGDC-STD-018-2012).

Feitoza BM, Rosa RS and Rocha LA. 2005. Ecology and zoogeography of deep-reef fishes in northeastern Brazil. *Bulletin of Marine Science.* **76(3):**725–742.

Ferrario F, Beck M, Storlazzi C, Micheli F, Shepard CC and Airoldi L. 2014. The effectiveness of coral reefs for coastal hazard risk reduction and adaptation. *Nature Communications* **5**:3794.

Figuerola Hernández M. 2020. *Coral reef community structure in La Parguera Natural Reserve ten years after the 2005-06 mass mortalities*. PhD Thesis, University of Puerto Rico. Mayagüez, PR.

Fisco D. 2016*. Reef fish spatial distribution and benthic habitat associations on the southeast Florida Reef Tract*. MSc. Thesis. Nova Southeastern University. Dania Beach, FL. http://nsuworks.nova.edu/occ_stuetd/408

Fisher WS, Davis WP, Quarles RL, Patrick J, Campbell JG, Harris PS, Hemmer BL and Parsons M. 2007. Characterizing Coral Condition Using Estimates of Three-dimensional Colony Surface Area. *Environmental Monitoring and Assessment* **125**:347–360.

Fisher WS, Fore LS, Hutchins A, Quarles RL, Campbell JG, LoBue C and Davis W. 2008. Evaluation of stony coral indicators for coral reef management. *Marine Pollution Bulletin* **56**:1737–1745.

Fisher WS, Fore LS, Oliver LM, LoBue C, Quarles RL, Campbell JG, Harris PS, Hemmer BL, Vickery S, Parsons M, Hutchins A, Bernier K, Rodriguez D and Bradley P. 2014. Regional status assessment of stony corals in the U.S. Virgin Islands. *Environmental Monitoring and Assessment* **186:**7165–7181.

Fisher WS, Vivian DN, Campbell J, LoBue C, Hemmer RL, Wilkinson S, Harris P, Santavy DL, Parsons M, Bradley P, Humphrey A, Oliver LM and Harwell L. 2019. Biological Assessment of Coral Reefs in Southern Puerto Rico: supporting coral reef protection under the U.S. clean water act. *Coastal Management* **47**:429–452.

Fisher WS. 2007. *Stony coral rapid bioassessment protocol*. US Environmental Protection Agency. EPA/600/R-06/167, July 2007. Office of Research and Development, Washington, DC.

Fitt WK, Brown BE, Warner ME and Dunne RP. 2001. Coral bleaching: interpretation of thermal tolerance limits and thermal thresholds in tropical corals. *Coral reefs.* **20(1):**51–65.

Fore LS, Fisher WS and Davis WS. 2006a. *Bioassessment Tools for Stony Corals: Monitoring Approaches and Proposed Sampling Plan for the U.S. Virgin Islands*. U.S. EPA, Office of Environmental Information. EPA-260-R-06-003p. 24.

Fore LS, Fisher WS and Davis WS. 2006b. *Bioassessment Tools for Stony Corals: Field Testing of Monitoring Protocols in the US Virgin Islands (St. Croix)*. U.S. EPA, Office of Environmental Information EPA-260-R-06-004p. 46.

Forman RT. 1995. Some general principles of landscape and regional ecology. *Landscape ecology.* **10(3):**133–142.

Forman RTT and Godron M. 1986. *Landscape ecology.* John Wiley, New York.

Frias-Lopez J, Klaus JS, Bonheyo GT and Fouke BW. 2004. Bacterial community associated with black band disease in corals. *Applied and Environmental Microbiology* **70(10):** 5955–5962.

Frias-Lopez J, Zerkle AL, Bonheyo GT and Fouke BW. 2002. Partitioning of bacterial communities between seawater and healthy, black band diseased, and dead coral surfaces. *Applied and Environmental Microbiology* **68(5):**2214–2228.

Friedlander AM and DeMartini EE. 2002. Contrasts in density, size, and biomass of reef fishes between the northwestern and the main Hawaiian islands: the effects of fishing down apex predators. *Marine Ecology Progress Series.* **230:**253–264.

Friedlander AM and Parrish JD. 1998. Habitat characteristics affecting fish assemblages on a Hawaiian coral reef. *Journal of Experimental Marine Biology and Ecology* **224**:1–30.

Friedlander AM, Brown EK, Jokiel PL, Smith WR and Rodgers KS. 2003. Effects of habitat, wave exposure, and marine protected area status on coral reef fish assemblages in the Hawaiian archipelago. *Coral Reefs* **22:**291–305.

Friedlander AM, Monaco ME, Clark R, Pittman SJ, Beets J, Boulon R, Callender R, Christensen J, Hile SD, Kendall MS. 2013. Fish movement patterns in Virgin Islands national park, Virgin Islands coral reef national monument and adjacent waters. NOAA Technical Memorandum NOS NCCOS:172. National Oceanic and Atmospheric Administration, Silver Spring, MD, USA

Frisch AJ, Ireland M, Rizzari JR, Lönnstedt OM, Magnenant KA, Mirbach CE and Hobbs JPA. 2016. Reassessing the trophic role of reef sharks as apex predators on coral reefs. *Coral Reefs* **35:** 459–472.

Froese R, Pauly D. 2002. FishBase: a global information system on fishes. *World Wide Web electronic publication.* www.fishbase.org.

Fuess LE, Eisenlord ME, Closek CJ, Tracy AM, Mauntz R, Gignoux-Wolfsohn S, Moritsch MM, Yoshioka R, Burge CA, Harvell CD and Friedman CS. 2015. Up in arms: immune and nervous system response to sea star wasting disease. *PLoS One.* **10(7):**e0133053.

Fulford RS, Peterson MS and Grammer PO. 2011. An ecological model of the habitat mosaic in estuarine nursery areas: Part I—Interaction of dispersal theory and habitat variability in describing juvenile fish distributions. *Ecological modelling.* **222(17):**3203–3215.

Furnas MJ. 2003. Catchments and corals: terrestrial runoff to the Great Barrier Reef. Australian Institute of Marine Science, Townsville, Australia.

Gabrié C, Vasseur P, Randriamiarana H, Maharavo J and Mara E. 2000. The coral reefs of Madagascar. Coral Reefs of the Indian Ocean. Their Ecology and Conservation. (eds) TR McClanahan, CRC Sheppard and DO Obura. pp. 411–444.

Galzin R, Planes S, Dufour V and Salvat B. 1994. Variation in diversity of coral reef fish between French Polynesian atolls. *Coral Reefs.* **13(3):**175–80.

García-Cagide AR. 2001. Reproductive patterns of fishes of the Cuban shelf. In *Ecology of the Marine Fishes of Cuba,* (eds.) R. Claro, KC Lindeman and LR Parenti. pp. 73–114.

García-Sais J, Appeldoorn R, Battista T, Bauer L, Bruckner A, Caldow C, Carrubba L, Corredor J, Diaz E, Lilyestrom C and García-Moliner G. 2008. The state of coral reef ecosystems of Puerto Rico. *The state of coral reef ecosystems of the United States and Pacific Freely Associated States.* pp. 75–116.

García-Sais J, Castro R, Sabater J and Carlo M. 2004. *Monitoring of coral reef communities from Isla de Vieques, Puerto Rico*. Final Report submitted to the Department of Natural and Environmental Resources of Puerto Rico, San Juan, PR, p 118.

García-Sais J, Castro R, Sabater J and Carlo M. 2005. *Inventory and atlas of corals and coral reefs, with emphasis on deep-water coral reefs from the U. S. Caribbean EEZ (Puerto Rico and the United States Virgin Islands).* Final Report submitted to the Caribbean Fishery Management Council. Coral Grant 2003 NAO3NMF4410352, p 215.

García-Sais J, Castro R, Sabater J, Esteves R and Carlo M. 2006. *Monitoring of coral reef communities from natural reserves in Puerto Rico: Isla Desecheo, Rincon, Mayaguez Bay, Guánica, Ponce and Caja de Muerto*. Final Report submitted to DNER-NOAA, San Juan, PR, p 145.

García-Sais JR, Castro R, Clavell JS, Esteves R andd Carlo M. 2005. Monitoring of Coral Reef Communities at Isla Desecheo, Rincon, Mayaguez Bay, Guanica, Ponce and Isla Caja de Muertos, Puerto Rico. Final Report submitted to the Department of Natural and Environmental Resources (DNER), US Coral Reef National Monitoring Program, NOAA.

García-Sais JR, Castro R, Sabater Clavell J, Carlo M, Esteves R and Williams S. 2008. *Monitoring of coral reef communities at Isla Desecheo Isla de Mona, Rincón, Ponce, Isla Caja de Muerto, Guánica, and Mayaguez, 2007-08*. Final Report submitted to the

Department of Natural and Environmental Resources (DNER), U. S. Coral Reef National Monitoring Program, NOAA, 212 pp.

García-Sais JR, Castro R, Sabater J and Carlo M. 2004. *Monitoring of coral reef communities from Isla de Vieques, Puerto Rico, 2004*. Final Report submitted to the Department of Natural and Environmental Resources (DNER), U. S. Coral Reef National Monitoring Program, NOAA, 118 pp

García-Sais JR, Morelock R, Castro C, Goenaga J and Hernandez-Delgado E. 2003. Puerto rican Reefs: research síntesis, present tretas and management perspectives. Latin American Coral Reefs. J. Cortez (Ed.) *Elsevier Science.* pp. 111–130

García-Sais JR, Williams SM and Amirrezvani A. 2017. Mortality, recovery, and community shifts of scleractinian corals in Puerto Rico one decade after the 2005 regional bleaching event. *Peer J* **5**. doi: 10.7717/peerj.3611.

Garcia-Sais JR. 2010. Reef habitats and associated sessile-benthic and fish assemblages across a euphotic–mesophotic depth gradient in Isla Desecheo, Puerto Rico. *Coral Reefs.* **29(2):**277–288.

Gardner TA, Cote IM, Gill JA, Grant A and Watkinson AR. 2003. Long-term region-wide declines in Caribbean corals. *Science* **301:**958–960.

Gattuso JP, Hoegh-Guldberg O and Pörtner HO. 2014: Cross-chapter box on coral reefs. In: *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* (eds.) Field CB, Barros VR, Dokken DJ, Mach KJ, Mastrandrea MD, Bilir TE, Chatterjee M, Ebi KL, Estrada YO, Genova RC, Girma B, Kissel ES, Levy AN, MacCracken S, Mastrandrea PR and White LL. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 97–100.

Gerritsen J, Bouchard RW Jr, Zheng L, Leppo EW and Yoder CO. 2017. Calibration of the biological condition gradient in Minnesota streams: a quantitative expert-based decision system. *Freshwater Science* **36**:427–451.

Gessner MO and Chauvet E. 2002. A case for using litter breakdown to assess functional stream integrity. *Ecological Applications* **12(2):**498–510.

Gil-Agudelo DL, Smith GW and Weil E. 2006. The white band disease type II pathogen in Puerto Rico. *Revista de biologia tropical.* **54:**59–67.

Gilmour JP. 2004. Size-structures of populations of the mushroom coral *Fungia fungites*—The role of disturbance. *Coral Reefs* **23(4):** 493–504.

Gintert BE, Precht WF, Fura F, Rogers K, Rice M, Precht LL, D'Alessandro M, Croop J, Vilmar C and Robbart ML. 2019. Regional coral disease outbreak overwhelms impacts from a local dredge project. *Environmental Monitoring and Assessment* **191(10):1-39.**

Gladfelter EH, Monahan RK and Gladfelter WB. 1978. Growth rates of five reef-building corals in the northeastern Caribbean. *Bulletin of Marine Science* **28(4):** 728–734.

Gladfelter WB, Ogden JC and Gladfelter EH. 1980. Similarity and Diversity Among Coral Reef Fish Communities: Comparison between Tropical Western Atlantic (Virgin Islands) and Tropical Central Pacific (Marshall Island) Patch Reefs. *Ecology* **61(5):** 1156–1168.

Gladfelter WB. 1982. White-band disease in *Acropora palmata*: Implications for the structure and growth of shallow reefs. *Bulletin of Marine Science* **32(2):** 639–643.

Glynn PW and D'Croz L. 1990. Experimental evidence for high temperature stress as the cause of El Niño-coincident coral mortality. *Coral reefs*. **8(4)**:181–191.

Glynn PW, Mate JL, Baker AC and Calderon MO. 2001. Coral bleaching and mortality in Panama and Ecuador during the 1997–1998 El Niño-Southern Oscillation Event: spatial/temporal patterns and comparisons with the 1982–1983 event. *Bulletin of Marine Science* **69:** 79–109.

Glynn PW. 1988a. Coral bleaching and mortality in the tropical eastern Pacific during the 1982-83 El Niño warming event. In: *Mass bleaching of coral reefs in the Caribbean: a research strategy* (eds.) J. Ogden and R. Wicklund, U.S. Dept. of Commerce. pp. 42– 45.

Glynn PW. 1988b. El Niño warming, coral mortality and reef framework destruction by echinoid bioerosion in the eastern Pacific. *Galaxea* **7:** 129–160.

Glynn PW. 1991. Coral reef bleaching in the 1980s and possible connections with global warming. Trends in Ecology and Evolution **6(6)**:175–179.

Glynn PW. 1993. Coral reef bleaching: ecological perspectives. *Coral Reefs* **12(1):** 1–17.

Glynn PW. 2012. Global Warming and Widespread Coral Mortality: Evidence of First Coral Reef Extinctions. In: *Saving a Million Species*. (eds.) Hannah L. Island Press/Center for Resource Economics. https://doi.org/10.5822/978–1-61091-182-5_7

Goenaga C and Boulon Jr RH. 1992. *The State of Puerto Rican and U.S. Virgin Islands Corals: An Aid to Managers*. Report submitted to the Caribbean Fishery Management Council, Hato Rey, P.R. 66 pp.

Goenaga C and Cintrón G. 1979. *Inventory of the Puerto Rican Coral Reef*s. Report submitted to the Coastal Zone Management of the Department of Natural Resources, San Juan, P.R. 190 pp.

Golbuu Y, Fabricius K, Victor S, Richmond RH. 2008. Gradients in coral reef communities exposed to muddy river discharge in Pohnpei, Micronesia. *Estuarine, Coastal and Shelf Science* 76(1):14–20.

Goodwin NB, Grant A, Perry AL, Dulvy NK and Reynolds JD. 2006. Life history correlates of density-dependent recruitment in marine fishes. *Canadian Journal of Fisheries and Aquatic Sciences.* **63(3):**494–509.

Goreau TF and Land LS. 1974. Fore-reef morphology and depositional processes, north Jamaica. In: *Reefs in Time and Space. (ed.) Laporte, L.F.* Society of Paleontologists and Mineralogists Special Publication 18. pp. 77– 89.

Goreau TF. 1959. The ecology of Jamaican coral reefs. I. Species composition and zonation. *Ecology* **40:**67–90.

Goreau TJ, Hayes RH, Clark JW, Basta DJ and Robertson CN. 1992. Elevated Sea Surface Temperatures Correlate with Caribbean Coral Reef Bleaching. In: *A Global Warming Forum: Scientific, Economic, and Legal Overview*. Geyer RA. (Ed.). CRC Press, Boca Raton, Florida USA, Chapter 9, pp. 225–255.

Graham NAJ and Nash KL. 2013. The importance of structural complexity in coral reef ecosystems *Coral Reefs* **32:**315–326.

Graham RT and Castellanos DW. 2005. Courtship and spawning behaviors of carangid species in Belize. *Fishery Bulletin.* **103(2):**426–432.

Gratwicke B and Speight MR. 2005a. Effects of habitat complexity on Caribbean marine fish assemblages. *Marine Ecology Progress Series* **292**:301–310.

Gratwicke B and Speight MR. 2005b. The relationship between fish species richness, abundance and habitat complexity in a range of shallow tropical marine habitats. *Journal of Fish Biology* **66**:650–667.

Gratwicke B, Petrovic C and Speight MR. 2006. Fish distribution and ontogenetic habitat preferences in non-estuarine lagoons and adjacent reefs. *Environmental Biology of Fishes.* **76(2–4):**191–210.

Green AL. 1996. Spatial, temporal and ontogenetic patterns of habitat use by coral reef fishes (Family Labridae). *Marine Ecology Progress Series* **133**:1–11.

Green D, Edmunds P and Carpenter R. 2008. Increasing relative abundance of *Porites astreoides* on Caribbean reefs mediated by an overall decline in coral cover. *Marine Ecology Progress Series* **359:** 1–10. doi: 10.3354/meps07454.

Greenslade PJ. 1983. Adversity selection and the habitat templet. *The American Naturalist.* **122(3):**352–365.

Greenstein BJ, Curran HA and Pandolfi JM. 1998. Shifting ecological baselines and the demise of Acropora cervicornis in the western North Atlantic and Caribbean Province: a Pleistocene perspective. *Coral Reefs.* **17(3):**249–261.

Grigg RW. 1994. Effects of sewage discharge, fishing pressure and habitat complexity on coral ecosystems and reef fishes in Hawaii. *Marine Ecology Progress Series.* Oldendorf. **103(1):**25–34.

Grime JP and Pierce S. 2012. The evolutionary strategies that shape ecosystems. John Wiley & Sons, Ltd, Oxford.

Grime JP. 1977. Evidence for the existence of three primary strategies in plants and its relevance to ecological and evolutionary theory. *The American Naturalist.* **111(982):**1169–94.

Grober-Dunsmore R, Frazer TK, Lindberg WJ and Beets J. 2007. Reef fish and habitat relationships in a Caribbean seascape: the importance of reef context. *Coral Reefs.* **26(1):**201–16.

Groner ML, Maynard J, Breyta R, Carnegie RB, Dobson A, Friedman CS, Froelich B, Garren M, Gulland FM, Heron SF and Noble RT. 2016. Managing marine disease emergencies in an era of rapid change. Philosophical Transactions of the Royal Society B: *Biological Sciences.* **371(1689):**20150364.

Grottoli AG, Rodrigues LJ and Palardy JE. 2006. Heterotrophic plasticity and resilience in bleached corals. *Nature* **440:** 1186–1189.

Guest JR, Baird AH, Goh BP and Chou LM. 2005. Reproductive seasonality in an equatorial assemblage of scleractinian corals. *Coral Reefs.* **24(1):**112–116.

Halpern BS. 2004. Are mangroves a limiting resource for two coral reef fishes? *Marine Ecology Progress Series.* **272:**93–98.

Harmelin-Vivien H. 1992. Impact of human activities on coral reef fish communities in French Polynesia. *Cybium* **16:** 279−289.

Harrison PL and Wallace CC. 1990. Reproduction, dispersal and recruitment of scleractinian corals. Coral Reefs. Chapter 7 in: *Ecosystems of the World* (ed.) Z. Dubinsky. Elsevier, Amsterdam. pp. 132–207.

Harrison PL and Booth DJ. 2007. Coral reefs: naturally dynamic and increasingly disturbed ecosystems. In: *Marine ecology*. (eds.) Connell SD, Gillanders BM. Oxford University Press, Oxford, pp. 316–377

Harrison PL and Wallace CC. 1990. Reproduction, dispersal and recruitment of scleractinian corals. In: *Ecosystems of the world: coral reefs* (ed) Dubinsky Z, Elsevier, Amsterdam **25**:133–207

Harrison PL. 2011. Sexual Reproduction of Scleractinian Corals. In *Coral Reefs: An Ecosystem in Transition* pp. 1–552.

Harrison TD and Whitfield AK. 2004. A multi-metric fish index to assess the environmental condition of estuaries. *Journal of Fish Biology* **65**:683–710.

Harvell CD, Altizer S, Cattadori IM, Harrington L and Weil E. 2009. Climate Change and Wildlife Diseases: When Does the Host Matter the Most? *Ecology* **90(4):**912–920.

Harvell CD, Kim K, Burkholder J, Coldwell RR, Epstein PR. Grimes DJ, Hoffman EE, Lipp EK, Osterhaus ADME, Overstreet RM, Porter J, Smith GW and Vasta GR. 1999. Emerging marine diseases: Climate links and anthropogenic factors. *Science* **285:**1505– 1510.

Harvell CD, Mitchell CE, Ward JR, Altizer S, Dobson AP, Ostfeld RS, Samuel MD. 2002. Climate warming and disease risks for terrestrial and marine biota. Science **296(5576)**:2158–2162.

Harvell D, Altizer S, Cattadori IM, Harrington L and Weil E. 2009. Climate change and wildlife diseases: When does the host matter the most? *Ecology* **90(4):**912–930.

Harvell D, Jordan-Dahlgren E, Merkel S, Rosenberg E, Raymundo L, Smith G, Weil E and Willis B. 2007. Coral disease, environmental drivers, and the balance between coral and microbial associates. *Oceanography* **20:**172–195.

Harvell D, Mitchell CE, Ward JR, Altizer S, Dobson A, Ostfeld RS and Samuel MD. 2002. Climate warming and disease risks for terrestrial and marine biota. *Science* **296**:2158–2162.

Hastings A. 2008. Editorial–an ecological theory journal at last. *Theoretical Ecology.* **1(1):**1–4.

Hausmann S, Charles DF, Gerritsen J and Belton TJ. 2016. A diatom-based Biological Condition Gradient (BCG) approach for assessing impairment and developing nutrient criteria for streams. *Science of the Total Environment* **562**: 914–927

Hawkins CP, Norris RH, Hogue JN and Feminella JW. 2000. Development and evaluation of predictive models for measuring the biological integrity of streams. *Ecological Applications* **10:**1456–1477.

Hawkins JP and Roberts CM. 2004. Effects of Artisanal Fishing on Caribbean Coral Reefs. *Conservation Biology* **18**:215–226.

Heyman WD and Kjerfve B. 2008. Characterization of transient multi-species reef fish spawning aggregations at Gladden Spit, Belize. *Bulletin of Marine Science* **83**:531–551.

Hay ME. 1984. Patterns of fish and urchin grazing on Caribbean coral reefs: are previous results typical? *Ecology* **65**:446–454.

Hay ME. 1991. Fish-seaweed interactions on coral reefs: effects of herbivorous fishes and adaptations of their prey. In: *The ecology of coral reef fishes*. (ed.) Sale PF. Academic Press, New York, pp. 96—119.

Heithaus MR. 2007. Nursery areas as essential shark habitats: a theoretical perspective. In: American Fisheries Society Symposium. American Fisheries Society. **50**:3

Hernández Delgado EA, Hutchinson-Delgado Y, Laureano R, Hernández-Pacheco R, Ruíz-Maldonado TM, Oms J, Díaz PL. 2010. *Sediment stress, water turbidity, and sewage pollution associated to rapid degradation of Federal Designated Critical Habitats of the threatened Elkhorn Coral (Acropora palmata) in Vega Baja. PR* Technical report submitted to National Oceanic and Atmospheric Administration Law Enforcement Office, Guaynabo, Puerto Rico.

Hernández R, Sherman C, Weil E and Yoshioka P. 2009. Spatial and temporal patterns in reef sediment accumulation and composition, southwestern insular shelf of Puerto Rico. *Caribbean Journal of Science.* **45(2–3):**138–50.

Hernández Delgado EA, Hutchinson-Delgado Y, Laureano R, Hernández-Pacheco R, Ruíz-Maldonado TM, Oms J, Díaz PL. 2010. *Sediment stress, water turbidity, and sewage pollution associated to rapid degradation of Federal Designated Critical Habitats of the threatened Elkhorn Coral (Acropora palmata) in Vega Baja. PR.* Technical report submitted to National Oceanic and Atmospheric Administration Law Enforcement Office, Guaynabo, Puerto Rico.

Hernández-Delgado EA, Toledo C, Claudio HJ, Lassus J, Lucking MA, Fonseca J, Hall K, Rafols J, Horta H and Sabat A. 2006. *Spatial and taxonomic patterns of coral bleaching and mortality in Puerto Rico during year 2005*. In: NOAA-NESDIS-CRWP. NOAA. U. S. Virgin Islands, St. Croix, USA.

Heron SF, Maynard JA, Van Hooidonk R and Eakin CM. 2016. Warming trends and bleaching stress of the world's coral reefs 1985–2012. *Scientific reports.* **6:**38402.

Heyman WD and Kjerfve B. 2008. Characterization of transient multi-species reef fish spawning aggregations at Gladden Spit, Belize. *Bulletin of Marine Science.* **83(3):**531–51.

Hixon MA and Beets JP. 1989. Shelter characteristics and Caribbean fish assemblages: experiments with artificial reefs. *Bulletin of Marine Science.* **44(2):**666–680.

Hixon MA and Brostoff WN. 1983. Damselfish as keystone species in reverse: intermediate disturbance and diversity of reef algae. *Science.* **220(4596):**511–513.

Hobson RD. 1972. Surface roughness in topography: quantitative approach. *In*: *Spatial analysis in geomorphology*. (ed.) Chorley, RJ, London: Methuen and Co., Ltd., p. 221–245.

Hodgson G and Dixon, J. A. 1988. Logging versus fisheries and tourism in Palawan. *Occasional papers of the East-West Environment and Policy Institute, Honolulu*. **7**:1–95.

Hoegh-Guldberg O and Smith GJ. 1989. The effect of sudden changes in temperature, light and salinity on the population density and export of zooxanthellae from the reef corals Stylophora pistillata Esper and Seriatopora hystrix Dana. *Journal of Experimental Marine Biology and Ecology* **129:**279–303.

Hoegh-Guldberg O and Bruno JF. 2010. The impact of climate change on the world's marine ecosystems. *Science* **328(5985)**:1523–1528. doi:10.1126/science.1189930

Hoegh-Guldberg O, Cai R, Poloczanska ES, Brewer PG, Sundby S, Hilmi K, Fabry VJ, Jung S, Skirving W, Stone DA, and Burrows MT. 2014. The Ocean. In: *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part B: Regional Aspects*. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. (eds) VR Barros, CB Field, DJ Dokken, MD Mastrandrea, KJ Mach, TE Bilir, M Chatterjee, KL Ebi, YO Estrada, RC Genova, B Girma, ES Kissel, AN Levy, S MacCracken, PR Mastrandrea, and LL White.Cambridge, UK; New York, NY: Cambridge University Press. pp. 1655–1731.

Hoegh-Guldberg O, Mumby PJ, Hooten AJ, Steneck RS, Greenfield P, Gomez E, Harvell CD, Sale PF, Edwards AJ, Caldeira K, Knowlton N, Eakin CM, Iglesias- Prieto R, Muthiga N, Bradbury RH, Dubi A and Hatziolos ME. 2007: Coral reefs under rapid climate change and ocean acidification. *Science* **318**(**5857**):1737–1742.

Hoegh-Guldberg O, Ortiz JC and Dove S. 2011. The future of coral reefs. *Science* **334:** 1494–1495.

Hoegh-Guldberg O, Poloczanska ES, Skirving W and Dove S. 2017. Coral reef ecosystems under climate change and ocean acidification. *Frontiers in Marine Science* **4**.

Hoegh-Guldberg O. 1999. Climate change, coral bleaching and the future of the world's coral reefs. *Marine and Freshwater Research* **50**:839–866.

Hoegh-Guldberg O. 2005. Low coral cover in a high-CO2 world. *Journal of Geophysical Research: Oceans.* **110:**C09S06.

Hoegh-Guldberg O. 2011. Coral reef ecosystems and anthropogenic climate change. *Regional Environmental Change* **11**:215–227.

Hoegh-Guldberg O. 1999. Climate change, coral bleaching and the future of the world's coral reefs. *Marine and Freshwater Research* **50(8):**839–866. doi:10.1071/MF99078

Holbrook SJ, Brooks AJ and Schmitt RJ. 2002a. Predictability of fish assemblages on coral patch reefs. *Marine and Freshwater Research* **53:** 181–188.

Holbrook SJ, Brooks AJ and Schmitt RJ. 2002b. Variation in structural attributes of patch-forming corals and in patterns of abundance of associated fishes. *Marine and Freshwater Research* **53:** 1045–1054.

Homer CG, Dewitz JA, Yang L, Jin S, Danielson P, Xian G, Coulston J, Herold ND, Wickham J, and Megown K. 2015. Completion of the National Land Cover Database for the conterminous United States – representing a decade of land cover change information. *Photogrammic Engineering and Remote Sensing* **81:** 345–354.

Hoogenboom MO, Campbell DA, Beraud E, DeZeeuw K and Ferrier-Pages C. 2012. Effects of light, food availability and temperature stress on the function of photosystem II and photosystem I of coral symbionts. *PLoS one.* **7(1):**e30167.

Horn MH. 1989. Biology of marine herbivorous fishes. *Oceanography and Marine Biology.* **27:**167–272.

Hubbard D, Ramirez W, Cuevas D, Erickson T and Estep A. 2009. Holocene reef accretion along the north side of Bahia Enriquillo (western Dominican Republic): Unique insights into patterns of reef development in response to sea-level rise. *Proceedings of the 11th International. Coral Reef Symposium* **1:**43–47.

Hubbard DK, Burke RB, Gill IP, Ramirez WR and Sherman C. 2008. Coral reef geology: Puerto Rico and the US Virgin Islands. In: *Coral reefs of the USA.* (eds.) Riegl B, Dodge R. Springer, Dordrecht, pp 263–302.

Hubbard DK, Gladfelter EH and Bythell JC. 1993. Comparison of biological and geological perspectives of coral-reef community structure at Buck Island, U.S. Virgin Islands. pp. 201–207. In: *Proceedings of the Colloquium on Global aspects of coral reefs: health hazards, and history*. (ed.) RN Ginsburg. Rosentiel School of Marine and Atmospheric Sciences, University of Miami. Miami, FL. 400 pp.

Hubbard DK. 1997. Reefs as dynamic systems. In: *Life and Death of Coral Reefs*. (ed.) Birkeland C.. Chapman and Hall Publishing, New York. pp. 43–67.

Hubbard JA. 1973. Sediment-shifting experiments: a guide to functional behavior in colonial corals. *Animal colonies*. Dowden, Hutchinson & Ross, Stroudsburg. pp. 31–42.

Hudson JH and Robbin DM. 1980. Effects of drilling mud on the growth rate of the reef-building coral, Montastrea annularis. *Elsevier Oceanography Series*. **27**:455–470.

Hughes RM and Peck DV. 2003. Acquiring Data for Large Aquatic Resource Surveys: The Art of Compromise Among Science, Logistics, and Reality. *Journal of the North American Benthological Society* **27(4):** 837–859.

Hughes TP and Connell JH. 1987. Population dynamics based on size or age? A reef-coral analysis. *The American Naturalist* **129(6):** 818–829.

Hughes TP and Connell JH. 1999. Multiple stressors on coral reefs: a long-term perspective. *Limnology and Oceanography* **44:**932–940.

Hughes TP and Jackson JBC. 1985. Population dynamics and life histories of foliaceous corals. *Ecological Monographs* **55(2):**141–166.

Hughes TP and Tanner JE. 2000. Recruitment failure, life histories, and long-term decline of Caribbean corals. *Ecology* **81**:2250–2263.

Hughes TP, Anderson K, Connolly S, Heron S, Kerry J, Lough J, Baird A, Baum J, Berumen M, Bridge T, Claar D, Eakin CM, Gilmour J, Graham N, Harrison H, Hobbs JP, Hoey A, Hoogenboom M, Lowe R, McCulloch M, Pandolfi J, Pratchett M, Schoepf V, Torda G and Wilson S. 2018. Spatial and temporal patterns of mass bleaching of corals in the Anthropocene. *Science* **359(6371):**80–83.

Hughes TP, Baird AH, Bellwood DR, Card M, Connolly SR, Folke C, Grosberg R, Hoegh-Guldberg O, Jackson JBC, Kleypas J, Lough JM, Marshall P, Nyström M, Palumbi SR, Pandolfi JM, Rosen B and Roughgraden J. 2003. Climate change, human impacts, and the resilience of coral reefs. *Science* **301(5635)**:929–933.

Hughes TP, Kerry JT, Álvarez-Noriega M, Álvarez-Romero JG, Anderson KD, Baird AH, Babcock RC, Beger M, Bellwood DR, Berkelmans R, Bride TC, Butler I, Byrne M, Neal E. Cantin NE, Comeau S, Connolly SR, Cumming GS, Dalton SJ, Diaz-Pulido G, Eakin CM, Figueira WF, Gilmour JP, Harrison HB, Hern SF, Hoey AS, Hobbs JA, Hoogenboom MO, Kennedy EV, Kuo C, Lough JM, Lowe RJ, Liu G, McCulloch MT, Malcolm HA, McWilliam MJ, Pandolfi JM, Pears RJ, Pratchett MS, Schoepf V, Simpson T, Skirvig WJ, Sommer B, Tora G, Wachenfeld DR, Willis BL and Wilson SK. 2017. Global warming and recurrent mass bleaching of corals. *Nature* **543 (7645):**373–377.

Hughes TP, Kerry T and Simpson T. 2018. Large-scale bleaching of corals on the Great Barrier Reef. *Ecology* **99:**501.

Hughes TP, Rodrigues MJ, Bellwood DR, Ceccarelli D, Hoegh-Guldberg O, McCook L, Moltschaniwskyj N, Pratchett MS, Steneck RS and Willis B. 2007. Phase shifts, herbivory, and the resilience of coral reefs to climate change. *Current Biol*ogy **17**:360–365.

Hughes TP. 1984. Population dynamics based on individual size rather than age—A general model with a reef coral example. *The American Naturalist* **123(6):**778–795.

Hughes TP. 1994. Catastrophes, phase shifts, and large-scale degradation of a Caribbean coral reef. *Science* **265**:1547– 1551.

Humann, P and N. DeLoach. 2003. *Reef fish identification*. Enlarged 3rd ed. Jacksonville, New World Publications, Inc., 481pp.

Ibelings BW, Vonk M, Los HFJ, Van Der Molen DT and Mooij WM. 2003. Fuzzy modeling of Cyanobacterial surface waterblooms: validation with NOAA-AVHRR satellite images. *Ecological Applications* **13**:1456–1472.

Idjadi JA and Edmunds PJ. 2006. Scleractinian corals as facilitators for other invertebrates on a Caribbean reef. *Marine Ecology Progress Series* **319:** 17–127.

Intergovernmental Panel on Climate Change (IPCC). 2014. Climate change 2014—Synthesis report, contribution of working groups I, II and III to the 5th assessment report of the Intergovernmental Panel on Climate Change. In: Intergovernmental Panel on Climate Change: Geneva, Switzerland, (eds.) Pachauri RK and Meyer LA. 167 pp.

Ionnidou IA, Paraskevopoulos S and Tzionas P. 2003. An interactive computer graphics interface for the introduction of fuzzy inference in environmental education. *Interacting with Computers* **18(4)**:683–708.

Irvine GV. 1980. Fish as Farmers-an Experimental-Study of Herbivory in a Territorial Coral-Reef Damselfish. *American Zoologist* **20(4)**:822–822.

Jackson J, Donovan M, Cramer K and Lam V (eds). 2014. *Status and trends of Caribbean coral reefs—1970–2012*. Gland, Switzerland, Global Coral Reef Monitoring Network, International Union for Conservation of Nature, 306 pp.

Jackson JB and Sala E. 2001. Unnatural Oceans. *Scientia Marina*, **65(S2)**:273–281.

Jackson JBC, Kirby MX, Berger WH, Bjorndal KA, Botsford LW, Bourque BJ, Bradbury RH, Cooke R, Erlandson J, Estes JA, Hughes TP, Kidwell S, Lange CB, Lenihan HS, Pandolfi JM, Peterson CH, Steneck RS, Tegner MJ and Warner RR. 2001. Historical overfishing and the recent collapse of coastal ecosystems. *Science* **293**:629–637.

Jackson JBC. 1977. Competition on marine hard substrate—The adaptive significance of solitary and colonial strategies. *The American Naturalist* **111(980)**:743–767.

Jackson JBC. 1997. Reefs since Columbus. *Coral Reefs* **16**: S23–S32.

Jameson SC, Erdmann MV, Karr JR and Potts KW. 2001. Charting a course toward diagnostic monitoring: a continuing review of coral reef attributes and a research strategy for creating coral reef indexes of biotic integrity. *Bulletin of Marine Science.* **69(2):**701–44.

Järvenpää M and Lindström K. 2004. Water turbidity by algal blooms causes mating system breakdown in a shallow-water fish, the sand goby *Pomatoschistus minutus*. *Proceedings of the Royal Society of London. Series B: Biological Sciences.* **271(1555):**2361–2365.

Jennings S and Polunin NV. 1997. Impacts of predator depletion by fishing on the biomass and diversity of non-target reef fish communities. *Coral reefs.* **16(2):**71–82.

Jennings S, Reynolds JD and Mills SC. 1998. Life history correlates of responses to fisheries exploitation. *Proceedings of the Royal Society of London. Series B: Biological Sciences.* **265(1393):**333–339.

Jensen PR, Harvell CD, Wirtz K and Fenical W. 1996. Antimicrobial activity of extracts of Caribbean gorgonian corals. *Marine Biology.* **125(2):**411–419.

Johannes RE. 1978. Reproductive strategies of coastal marine fishes in the tropics. *Environmental Biology of Fishes* **3**:65–84.

Jokiel PL and Coles SL. 1977. Effects of temperature on the mortality and growth of Hawaiian reef corals. *Marine Biology.* **43(3):**201–208.

Jones GP, Almany GR, Russ GR, Sale PF, Steneck RS and Van Oppen MJ. 2009. Larval retention and connectivity among populations of corals and reef fishes: history, advances and challenges. *Coral Reefs.* **28:**307–325. doi**:** 10.1007/s00338-009-0469-9

Jones GP, McCormick MI, Srinivasan M, Eagle JV (2004) Coral decline threatens fish biodiversity. *Proceedings of the National Academy of Scien*ces **101:**8251–8253.

Jones R, Bessell-Browne P, Fisher R, Klonowski W and Slivkoff M. 2016. Assessing the impacts of sediments from dredging on corals. *Marine Pollution Bulletin* **102(1):**9–29.

Jones RJ, Berkelmans R and Oliver JK. 1997. Recurrent bleaching of corals at Magnetic Island (Australia) relative to air and seawater temperature. *Marine Ecology Progress Series* **158:**289–292.

Junjie RK, Browne NK, Erftemeijer PL and Todd PA. 2014. Impacts of sediments on coral energetics: partitioning the effects of turbidity and settling particles. *PLoS One.* **9(9):**e107195.

Jupiter S, Roff G, Marion G, Henderson M, Schrameyer V, McCulloch M, Hoegh-Guldberg O. 2008. Linkages between coral assemblages and coral proxies of terrestrial exposure along a cross-shelf gradient on the southern Great Barrier Reef. Coral Reefs **27(4)**:887–903.

Kaczmarsky LT, Draud M, and Williams EH. 2005. Is there a relationship between proximity to sewage effluent and the prevalence of coral disease? *Caribbean Journal of Science* **41(1)**:124–137.

Kahng SE, Garcia-Sais JR, Spalding HL, Brokovich E, Wagner D, Weil E, Hinderstein L and Toonen RJ. 2010. Community ecology of mesophotic coral reef ecosystems. *Coral Reefs* **29:**255–275.

Karr JR, Fausch K, Angermeier P, Yant P and Schlosser I. 1986. Assessing biological integrity in running waters: a method and its rationale. *Illinois Natural History Survey Special Publication* **5:**23.

Karr JR. 1991. Biological Integrity: A Long-Neglected Aspect of Water Resource Management. *Ecological Applications* **1 (1)**:66–84.

Karr JR and Chu EW. 1999. Restoring life in running waters: Better biological monitoring. Island Press, Washington, DC 206 pp.

Karr JR. 1991. Biological integrity: a long-neglected aspect of water resource management. *Ecological applications.* **1(1):**66–84.

Kemp DW, Thornhill DJ, Rotjan RD, Iglesias-Prieto R, Fitt WK and Schmidt GW. 2015. Spatially distinct and regionally endemic *Symbiodinium* assemblages in the threatened Caribbean reef-building coral *Orbicella faveolata*. *Coral Reefs* **34:**535–547.

Kendall MS, Kruer CR, Buja KR, Christensen JD, Finkbeiner M, Warner RA and Monaco ME. 2001. *Methods Used to Map the Benthic Habitats of Puerto Rico and the U.S. Virgin Islands*. NOAA Technical Memorandum 152. NOS NCCOS CCMA Silver Spring, MD.

Kilfoyle AK, Walker BK, Gregg K, Fisco DP and Spieler RE. 2017. *Southeast Florida Coral Reef Fishery-Independent Baseline Assessment: 2012-2016 Summary Report*. National Oceanic and Atmospheric Administration. 121 pp.

Kimmel JJ. 1985. *A characterization of Puerto Rican fish assemblages*. PhD Thesis, University of Puerto Rico, Mayagüez PR.

Kisabeth JK, Smith T, Primack A and Wilson K. 2014. *Cruise ship induced sediment resuspension characteristics in Charlotte Amalie Harbor and the West Gregerie Channel, St. Thomas, US Virgin Islands*. PhD Thesis, University of the Virgin Islands, St. Thomas, USVI.

Kleypas JA, Buddemeier RW and Gattuso JP. 2001. The future of coral reefs in an age of global change. *International Journal of Earth Sciences.* **90(2):**426–37.

Kleypas JA, Feely RA, Fabry VJ, Langdon C, Sabine CL, and Robbins LL. 2006. *Impacts of ocean acidification on coral reefs and other marine calcifiers: A guide for future research*. Report of a workshop held 18-20 April 2005, St. Petersburg, FL, sponsored by NSF, NOAA, and the US Geological Survey 88 pp.

Kleypas JA, McManus JW and Menez LAB. 1999. Environmental limits to coral reef development: Where do we draw the line? *American Zoologist* **39**:146–159.

Klir, GJ. 2004. Fuzzy logic: A specialized tutorial, In Fuzzy Logic in Geology (eds. Demicco, RV and Klir, GJ) (Elsevier Academic Press, San Diego 2004) pp. 11–61.

Knowlton N and Jackson JBC. 2008. Shifting baselines, local impacts, and global change on coral reefs. *PLoS Biology* **6**: e54.

Knowlton N, Lang JC and Keller BD. 1990. Case study of natural population collapse: Post hurricane predation on Jamaican staghorn corals. *Smithsonian Contributions to the Marine Sciences* **31:**1–25.

Knowlton N. 2001. The future of coral reefs. *Proceedings of the National Academy of Sciences USA* **98:**5419–5425.

Koenig C, Pauly D, Arreguin-Sanchez F, Coleman F, Munro JL, Balgos MC, Domeier ML. 1996. Reproductive biology of the gray snapper (*Lutjanus griseus*), with notes on spawning for other western Atlantic snappers (Lutjanidae). *Biology, fisheries and culture of tropical groupers and snappers*. pp. 189–201.

Kokita T and Nakazono A. 2001. Rapid response of an obligately corallivorous filefish *Oxymonacanthus longirostris* (Monacanthidae) to a mass coral bleaching event. *Coral Reefs.* **20(2):**155–158.

Koslow JA, Hanley F and Wicklund, R. 1988. Effects of fishing on reef fish communities at Pedro Bank and Port Royal Cays, Jamaica. *Marine Ecology Progress Series.* **43**: 201–212.

Kramer PA. 2003. Synthesis of coral reef health indicators for the western Atlantic: results of the AGRRA program (1997-2000). *Atoll Research Bulletin.* **496**:1–57.

Kuffner IB, Brock JC, Grober-Dunsmore R, Bonito VE, Hickey TD and Wright CW. 2007. Relationships between reef fish communities and remotely sensed rugosity measurements in Biscayne National Park, Florida, USA. *Environmental biology of fishes.* **78(1)**:71–82.

LaCommare KS, Self-Sullivan C and Brault S. 2008. Distribution and habitat use of Antillean manatees (Trichechus manatus manatus) in the Drowned Cayes area of Belize, Central America. *Aquatic Mammals.* **34(1):**35.

Lafferty KD and Hofmann EE. 2016. Marine disease impacts, diagnosis, fore-casting, management and policy. *Philosophical Transactions of the Royal Society B.* ***371:**20150200.*

Lang JC. 2003. Status of coral reefs in the western Atlantic: results of initial surveys, Atlantic and Gulf Rapid Reef Assessment (AGRRA) Program. *Atoll Research Bulletin* **496**: 1–630.

Larcombe P and Carter RM. 1998. Sequence architecture during the Holocene transgression: an example from the Great Barrier Reef shelf, Australia. *Sedimentary Geology.* **117(1-2):**97–121.

Lasker HR. 1980. Sediment rejection by reef corals: the roles of behavior and morphology in *Montastrea cavernosa* (Linnaeus). *Journal of Experimental Marine Biology and Ecology.* **47(1):**77–87.

Lassuy DR. 1980. Effects of "farming" behavior by *Eupomacentrus lividus* and *Hemiglyphidodon plagiometopon* on algal community structure. *Bulletin of Marine Science.* **30(1):**304–12.

Laverick JH, Andradi-Brown DA, Exton DA, Bongaerts P, Bridge TC, Lesser MP, Pyle RL, Slattery M, Wagner D and Rogers AD. 2016. To what extent do mesophotic coral ecosystems and shallow reefs share species of conservation interest? *Environmental Evidence.* **5(1):**16.

Leahy SM, McCormick MI, Mitchell MD and Ferrari MCO. 2011. To fear or to feed: the effects of turbidity on perception of risk by a marine fish. *Biology Letters* **7:** 811–813

Lefebvre LW, Reid JP, Kenworthy WJ and Powell JA. 1999. Characterizing manatee habitat use and seagrass grazing in Florida and Puerto Rico: implications for conservation and management. *Pacific Conservation Biology.* **5(4):**289–98.

Lesser MP, Bythell JC, Gates RD, Johnstone RW and Hoegh-Guldberg O. 2007. Are infectious diseases really killing corals? Alternative interpretations of the experimental and ecological data. *Journal of experimental marine biology and ecology.* **346(1-2):**36–44.

Lessios HA, Robertson, DR and Cubit JD 1984. Spread of *Diadema* mass mortality through the Caribbean. *Science*. **226(4672)**:335–337.

Lessios HA. 1988a. Mass mortality of *Diadema antillarum* in the Caribbean: what have we learned? *Annual Review of Ecology and Systemics* **19:** 371– 393.

Lessios HA. 1988b. Population dynamics of *Diadema antillarum* (Echinodermata: Echinoidea) following mass mortality in Panama. *Marine Biology* **99:** 515–526.

Lessios HA. 2005. *Diadema antillarum* populations in Panama twenty years following mass mortality. *Coral Reefs* **24(1)**:125–127.

Lessios HA. 2016. The Great *Diadema antillarum* Die-Off: 30 Years Later. *Annual review of marine science **8**:267–283.*

Letourneur Y, Kulbicki M and Labrosse P. 1998. Length-weight relationship of fishes from coral reefs and lagoons of New Caledonia: an update. *Naga, the ICLARM Quarterly.* **21(4):**39–46.

Levin RA, Voolstra CR, Weynberg KD and Van Oppen MJ. 2017. Evidence for a role of viruses in the thermal sensitivity of coral photosymbionts. *The International Society of Microbial Ecology Journal.* **11(3):**808–812.

Levitan DR. 1988. Algal-urchin biomass responses following mass mortality of *Diadema antillarum Philippi* at Saint John, U.S. Virgin Islands. *Journal of Experimental Marine Biology and Ecology* **119:** 167–178.

Lewis AR. 1997a. Recruitment and post-recruit immigration affect the local population size of coral reef fishes. *Coral Reefs* **16:** 139–149.

Lewis AR. 1997b. Effects of experimental coral disturbance on the structure of fish communities on large patch reefs. *Marine Ecology Progress Series* **161:** 31–50.

Lewis AR. 1998. Effects of experimental coral disturbance on the population dynamics of fishes on large patch reefs. *Journal of Experimental Biology and Ecology* **230 (1):** 91–110.

Lewis SM. 1986. The role of herbivorous fishes in the organization of a Caribbean fish community. *Ecological Monographs* **56(3):** 183–200.

Lindberg WJ, Frazer TK, Portier KM, Vose F, Loftin J, Murie DJ, Mason DM, Nagy B and Hart MK. 2006. Density-Dependent Habitat Selection and Performance by a Large Mobile Reef Fish. *Ecological Applications* **16(2):** 731–746

Lindeman KA, Pugliese R, Waugh GT and Ault JS. 2000. Developmental patterns within a multispecies reef fishery: management applications for essential fish habitats and protected areas. *Bulletin of Marine Science* **66(3):** 929–956.

Lindeman KC and DeMaria D. 2005. Juveniles of the Caribbean's largest coral reef snapper do not use reefs. *Coral Reefs*. **24(3)**:359–359.

Lindeman KC and Snyder DB. 1999. Nearshore hardbottom fishes of southeast Florida and effects of habitat burial caused by dredging. *Fishery Bulletin.* **97(3):**508–525.

Lindeman KC. 1997. *Development of grunts and snappers of southeast Florida: cross-shelf distributions and effects of beach management alternatives*. PhD Thesis, University of Miami, FL.

Lirman D, Schopmeyer S, Galvan V, Drury C, Baker AC and Baums IB. 2014. Growth dynamics of the threatened Caribbean staghorn coral Acropora cervicornis: influence of host genotype, symbiont identity, colony size, and environmental setting. *PloS one.* **9(9):**e107253.

Lirman D. 2001. Competition between macroalgae and corals: effect of herbivore exclusion and increased algal biomass on coral survivorship and growth. *Coral Reefs* **19:**392–399.

Lirman D. 2013. *Benthic Habitat: Coral and Hardbottom.* MARES - MARine and Estuarine goal Setting for South Florida. www.sofla-mares.org.

Liu G, Heron SF, Eakin CM, Muller-Karger FE, Vega-Rodriguez M, Guild LS, De La Cour JL, Geiger EF, Skirving WJ, Burgess TFR, Strong AE, Harris A, Maturi E, Ignatov A, Sapper J, Li J and Lynds S. 2014. Reef-scale thermal stress monitoring of coral ecosystems: new 5-km global products from NOAA coral reef watch. *Remote Sensing* **6:** 11579–11606 doi:10.3390/rs61111579.

Logan CA, Dunne JP, Eakin CM and Donner SD. 2014. Incorporating adaptive responses into future projections of coral bleaching. *Global Change Biology.* **20(1):**125–39.

López-Pérez RA, Calderon-Aguilera LE, Zepeta-Vilchis RC, López Pérez Maldonado I and López Ortiz AM. 2013. Species composition, habitat configuration and seasonal changes of coral reef fish assemblages in western Mexico. *Journal of Applied Ichthyology*, **29(2)**:437–448.

Lord KS, Lesneski KC, Bengtsson ZA, Kuhn KM, Madin J, Cheung B, Ewa R, Taylor JF, Burmester EM, Morey J and Kaufman L. 2020. Multi-year viability of a reef coral population living on mangrove roots suggests an important role for mangroves in the broader habitat mosaic of corals. *Frontiers in Marine Science.* **3(7)**:377.

Lough JM and Van Oppen MJ. 2009. Introduction: coral bleaching—patterns, processes, causes and consequences. In: *Coral Bleaching*. Springer, Berlin, Heidelberg. pp. 1–5

Loya Y and Sakai K. 2008. Bidirectional sex change in mushroom stony corals. *Proceedings of the Royal Society B: Biological Sciences.* **275(1649):**2335–2343.

Loya Y, Sakai K, Yamazato K, Nakano Y, Sambali H and Van Woesik R. 2001. Coral bleaching: the winners and the losers. *Ecology letters.* **4(2):**122–131.

Loya Y. 1976. Effects of water turbidity and sedimentation on the community structure of Puerto Rican corals. *Bulletin of Marine Science.* **26(4):**450–466.

Luckhurst BE and Luckhurst K. 1978. Analysis of substrate variables on coral reef fish communities. *Marine Biology* **49**:317–323.

Ma KY and Craig MT. 2018. An inconvenient monophyly: an update on the taxonomy of the groupers (Epinephelidae). *Copeia.* **106(3):**443–456.

MacArthur RH. 1972. Geographical ecology: patterns in the distribution of species. Harper & Row, New York.

Machemer EG, Walter III JF, Serafy JE and Kerstetter DW. 2012. Importance of mangrove shorelines for rainbow parrotfish *Scarus guacamaia*: habitat suitability modeling in a subtropical bay. *Aquatic Biology.* **15(1):**87–98.

Maina J, McClanahan TR, Venus V, Ateweberhan M, Madin J. 2010. Global gradients of coral exposure to environmental stresses and implications for local management. *PLoS One*. **6(8)**:e23064.

Mallela J, Roberts C, Harrod C and Goldspink CR. 2007. Distributional patterns and community structure of Caribbean coral reef fishes within a river-impacted bay. *Journal of Fish Biology* **70:**523−537.

Man A, Law R and Polunin NVC. 1995. Role of marine reserves in recruitment to reef fisheries: a metapopulation model. *Biological Conservation* **71**:197–204.

Mann P, Hippolyte JC, Grindlay NR and Abrams LJ. 2005. Neotectonics of southern Puerto Rico and its offshore margin. *Active tectonics and seismic hazards of Puerto Rico, the Virgin Islands, and offshore areas.* **385:**173-214.

Maragos JE. 1974. Reef corals of Fanning Island. *Pacific Science* **28:**247–255.

Maynard J, Van Hooidonk R, Eakin CM, Puotinen M, Garren M, Williams G, Heron SF, Lamb J, Weil E, Willis B and Harvell CD. 2015. Projections of climate conditions that increase coral disease susceptibility and pathogen abundance and virulence. *Nature Climate Change.* **5(7):**688–694.

McClanahan T, Graham NAJ, Calnan JM, and MacNeil MA. 2007. Toward pristine biomass: Reef fish recovery in coral reef marine protected areas in Kenya. *Ecological Applications* **17**:1055–1067.

McClanahan T, Weil E, Baird A. 2018. Impact of bleaching on coral reefs. *In: Coral bleaching: patterns, processes, causes and consequences, 2nd edn.* (eds.) van Oppen M, Lough JM. Springer, Berlin, pp 231–264

McClanahan TR, Ateweberhan M and Omukoto J. 2008. Long-term changes in coral colony size distributions on Kenyan reefs under different management regimes and across the 1998 bleaching event. *Marine Biology* **153:**755–768.

McClanahan TR, Weil E, Cortés J, Baird AH and Ateweberhan M. 2009. Consequences of coral bleaching for sessile reef organisms, chap. 8 In*: Coral bleaching—Patterns, processes, causes and consequences*. (eds.) van Oppen M and Lough J. Champaign, Ill., Springer-Verlag, *Ecological Studies* **205**:121–138.

McClanahan TR. 1994. Kenyan coral reef lagoon fish: effects of fishing, substrate complexity and sea urchins. *Coral Reefs* **13**:231–241.

McClanahan TR. 2017. Changes in coral sensitivity to thermal anomalies. *Marine Ecology Progress Series.* **570:**71–85.

McCook L, Jompa J and Diaz-Pulido G. 2001. Competition between corals and algae on coral reefs—A review of evidence and mechanisms. *Coral Reefs* **19:**400–417.

McCook LJ, Almany GR, Berumen ML, Day JC, Green AL, Jones GP, Leis JM, Planes S, Russ GR, Sale PF and Thorrold SR. 2009. Management under uncertainty: guide-lines for incorporating connectivity into the protection of coral reefs. *Coral Reefs.* **28(2):**353–366.

McCormick M. 1994. Comparison of field methods for measuring surface topography and their associations with a tropical reef fish assemblage. *Marine Ecology Progress Series* **112**:87–96.

McField M and Kramer PR. 2007. *Healthy Reefs for Healthy people: A Guide to Indicators of Reef Health and Social Well-being in the Mesoamerican Reef Region.* With contributions by M Gorrez and M McPherson. 208 pp.

McGill BJ, Enquist BJ, Weiher E and Westoby M. 2006. Rebuilding community ecology from functional traits. *Trends in ecology & evolution.* **21(4):**178–185.

McMahon KW, Berumen ML and Thorrold SR. 2012. Linking habitat mosaics and connectivity in a coral reef seascape. *Proceedings of the National Academy of Sciences.* **109(38):**15372–15376.

Meesters EH, Hilterman M, Kardinaal E, Keetman M and Bak RPM. 2001. Colony size-frequency distributions of scleractinian coral populations—Spatial and interspecific variation. *Marine Ecology Progress Series* **209:**43–54.

Meissner KJ, Lippmann T and Gupta AS. 2012. Large-scale stress factors affecting coral reefs: open ocean sea surface temperature and surface seawater aragonite saturation over the next 400 years. *Coral Reefs* **31:** 309–319.

Meyer JL, Castellanos-Gell J, Aeby GS, Häse CC, Ushijima B and Paul VJ. 2019. Microbial community shifts associated with the ongoing stony coral tissue loss disease outbreak on the Florida Reef Tract. *Frontiers in Microbiology.* **10:**2244.

Meynecke JO, Lee SY and Duke NC. 2008. Linking spatial metrics and fish catch reveals the importance of coastal wetland connectivity to inshore fisheries in Queensland, Australia. *Biological Conservation* **141**:981–996.

Miller GL and Lugo AE. 2009. *Guide to the ecological systems of Puerto Rico*. General Technical Report. IITF-GTR-35. San Juan, PR: U.S. Department of Agriculture, Forest Service, International Institute of Tropical Forestry. 437 pp.

Miller J, Muller E, Rogers C, Waara R, Atkinson A, Whelan KRT, Patterson M and Witcher B. 2009. Coral disease following massive bleaching in 2005 causes 60% decline in coral cover on reefs in the US Virgin Islands. *Coral Reefs* **28:** 925–937. doi: 10.1007/s00338-009-0531-7.

Miller J, Rogers CS and Waara R. 2003. Monitoring the coral disease plague type II on coral reefs in St. John, US Virgin Islands. Proc of the 30th Scientific Meeting of the Association of Marine Laboratories of the Caribbean, PR. *Revista de Biologia Tropical* **51:** 47–55.

Miller J, Waara R, Muller E and Rogers C. 2006. Coral bleaching and disease combine to cause extensive mortality on reefs in US Virgin Islands. *Coral Reefs* **25:** 418. doi: 10.1007/s00338-006-0125-6.

Miller M, Williams DE, Huntington BE, Piniak GA and Vermeij MJA. 2016, Decadal comparison of a diminishing coral community—A study using demographics to advance inferences of community status. *PeerJ* **4:** e1643.

Mora C. 2008. A clear human footprint in the coral reefs of the Caribbean. *Proceedings of the Royal Society of London B*. **275**:767–773.

Morelock J, Ramírez WR, Bruckner AW and Carlo M. 2001. Status of coral reefs southwest Puerto Rico. *Caribbean Journal of Science Special Publication No. 4.* 57 pp.

Moustaka M, Langlois TJ, McLean D, Bond T, Fisher R, Fearns P, Dorji P and Evan RD. 2018. The effects of suspended sediment on coral reef fish assemblages and feeding guilds of north-west Australia. *Coral Reefs* **37(3):** 659–673.

Moya A, Tambutté S, Tambutté E, Zoccola D, Caminiti N and Allemand D. 2006. Study of calcification during a daily cycle of the coral *Stylophora pistillata*: implications for light-enhanced calcification. *Journal of Experimental Biology.* **209(17):**3413–3419.

Mullen KM, Harvell CD, Alker AP, Dube D, Jordán-Dahlgren E, Ward JR and Petes LE. 2006. Host range and resistance to aspergillosis in three sea fan species from the Yucatan. *Marine Biology.* **149(6):**1355-1364.

Muller EM, Rogers CS, Spitzack AS and Van Woesik R. 2008. Bleaching increases likelihood of disease on *Acropora palmata* (Lamarck) in Hawksnest Bay, St. John, U.S. Virgin Islands. *Coral Reefs* **27:** 191–195.

Mumby PJ, Broad K, Brumbaugh DR, Dahlgren CP, Harborne AR, Hastings A, Holmes KE, Kappel CV, Micheli F and Sanchirico JN. 2008. Coral reef habitats as surrogates of species, ecological functions, and ecosystem services. *Conservation Biology* **22**: 941–951.

Mumby PJ, Dahlgren CP, Harborne AR, Kappel CV, Micheli F, Brumbaugh DR, Holmes KE, Mendes JM, Broad K, Sanchirico JN, Buch K, Box S, Stoffle RW and Gil AB. 2006. Fishing, trophic cascades, and the process of grazing on coral reefs. *Science* **311**: 98–101.

Mumby PJ, Edwards AJ, Arias-Gonzalez JE, Lindeman KC, Blackwell PG, Gall A, Gorczynska MI, Harborne AR, Pescod CL, Renken H, Wabnitz CC and Llewellyn G. 2004. Mangroves enhance the biomass of coral reef fish communities in the Caribbean. *Nature* **427**: 533–536.

Munday PL. 2001. Fitness consequences of habitat selection and competition among coral-dwelling fish. *Oecologia* **128:** 585–593. doi: 10.1007/s004420100690.

Muñiz-Castillo AI, Rivera-Sosa A, Chollett I, Eakin CM, Andrade-Gómez L, McField M and Arias-González JE. 2019. Three decades of heat stress exposure in Caribbean coral reefs: a new regional delineation to enhance conservation. *Scientific reports.* **9(1):**1–4.

Munro JL, Gaut VC, Thompson R and Reeson PH. 1973. The spawning seasons of Caribbean reef fishes. *Journal of Fish Biology.* **5(1):**69–84.

Munro JL. 1983. *Caribbean Coral Reef Fishery Resources*. WorldFish, 286 pp.

Murdoch TJ. 2007. *A Functional Group Approach for Predicting the Composition of Hard Coral Assemblages in Florida and Bermuda*. Ph.D. thesis, Department of Marine Science, University of South Alabama, AL.

Muscatine LE and Porter JW. 1977. Reef corals: mutualistic symbioses adapted to nutrient-poor environments. *Bioscience.* **27(7):**454–60.

Musick JA, Burgess G, Cailliet G, Camhi M, Fordham S. 2000. Management of sharks and their relatives (Elasmobranchii). *Fisheries*. **25(3)**:9–13.

Mydlarz LD, Holthouse SF, Peters EC and Harvell CD. 2008. Cellular responses in sea fan corals: granular amoebocytes react to pathogen and climate stressors. *PLoS one.* **3(3):**e1811.

Mydlarz LD, McGinty ES and Harvell CD. What are the physiological and immunological responses of coral to climate warming and disease? *Journal of Experimental Biology.* **213(6):**934–945.

Nadon MO and Sterling G. 2006. Field and Simulation Analyses of Visual Methods for Sampling Coral Cover. *Coral Reefs* **25:** 177–185. doi:10.1007/s00338-005-0074-5.

Nagelkerken I, Dorenbosch M, Verbeck WCEP, Cocheret de la Moriniere E, and van der Velde, G. 2000. Importance of shallow-water biotopes of a Caribbean bay for juvenile coral reef fishes: patterns in biotope association, community structure and spatial distribution. *Marine Ecology Progress Series* **202**: 175–192.

Nagelkerken I, Dorenbosch M, Verberk WCEP, Cocheret de la Moriniere E and van der Velde G. 2000. Importance of shallow-water biotopes of a Caribbean bay for juvenile coral reef fishes: patterns in biotope association and spatial distribution. *Marine Ecological Progress Series* **202:** 175–192.

Nagelkerken I, Sheaves M, Baker R and Connolly RM. 2015. The seascape nursery: a novel spatial approach to identify and manage nurseries for coastal marine fauna. *Fish and Fisheries* **16:** 362-371.

National Oceanic and Atmospheric Administration (NOAA). 2012. *Draft Management Report for 82 Corals Status Review under the Endangered Species Act: Existing Regulatory Mechanisms (per Endangered Species Act § 4(a)(1)(D), 16 U.S.C. § 1533(a)(1)(D)) and Conservation Efforts (per Endangered Species Act § 4(b)(1)(A), 16 U.S.C. § 1533(b)(1)(A))*. Pacific Islands Regional Office, National Marine Fisheries Service, 233 pp.

National Oceanic and Atmospheric Administration (NOAA). 2014a. *NOAA's State of the Coast website*. http://stateofthecoast.noaa.gov/

National Oceanic and Atmospheric Administration (NOAA). 2014b. *Belt Transect Fish Survey Protocol for Atlantic/ Caribbean*. Coral Reef Conservation Program, National Oceanic and Atmospheric Administration, 7 pp.

National Oceanic and Atmospheric Administration (NOAA). 2015a. *Belt Transect Fish Survey Protocol for the U.S. Caribbean and Flower Garden Banks National Marine Sanctuary*. National Coral Reef Monitoring Program (NCRMP) Coral Reef Conservation Program (CRCP), National Oceanic and Atmospheric Administration, 9 pp.

National Oceanic and Atmospheric Administration (NOAA). 2015e. *Recovery Plan for Elkhorn (Acropora palmata) and Staghorn (A. cervicornis) Corals*. Prepared by the Acropora Recovery Team for the National Marine Fisheries Service, Silver Spring, Maryland.

National Oceanic and Atmospheric Administration (NOAA). 2020. *Recovery Outline: Giant Manta Ray*. Accessed 7/20/20 at: https://www.fisheries.noaa.gov/resource/document/giant-manta-ray-recovery-outline

National Oceanic and Atmospheric Administration (NOAA). 2020. *Recovery Outline: Nassau Grouper*. Accessed 7/20/20 at: https://www.fisheries.noaa.gov/resource/document/nassau-grouper-recovery-outline

National Oceanic and Atmospheric Administration (NOAA). 2012. *Endangered and threatened wildlife and plants—Proposed listing determinations for 82 reef-building coral species—Proposed reclassification of Acropora palmata and Acropora cervicornis from threatened to endangered*. Federal Register **77(236)**: 73221–73261.

National Park Service (NPS) South Florida/Caribbean Network. 2019. *Coral Reef Monitoring in Virgin Islands National Park, Buck Island and Salt River, 2019*. Resource Brief. National Park Service.

Nemeth RS, Kadison E, Herzlieb S, Blondeau J and Whiteman E. 2006. Status of a yellowfin grouper (*Mycteroperca venenosa*) spawning aggregation in the U.S. Virgin Islands with notes on other species. *Proceedings of the Gulf and Caribbean Fisheries Institute* **57**: 543–558.

Neves LM, Teixeira-Neves TP, Pereira-Filho GH and Araújo FG. 2016. The farther the better: Effects of multiple environmental variables on reef fish assemblages along a distance gradient from river influences. *PLoS ONE* **11**: e0166679.

Newman MJH, Paredes GA, Sala S, and Jackson JBC. 2006. Structure of Caribbean coral reef communities across a large gradient of fish biomass. *Ecology Letters* **9**: 1216–1227.

Niemi GJ and McDonald ME. 2004. Application of Ecological Indicators. *Annual Review of Ecology, Evolution, and Systematics* **35 (1):** 89–111.

Nugues MM and Roberts CM. 2003. Partial mortality in massive reef corals as an indicator of sediment stress on coral reefs. *Marine Pollution Bulletin* **46**: 314–323.

Nugues MM, Smith GW, van Hooidonk RJ, Seabra MI and Bak RPM. 2004. Algal contact as a trigger for coral disease. *Ecology Letters* **7(10):** 919–923.

Obura D, Muthiga N and Watson M. 2000. Kenya. In: *Coral Reefs of The Indian Ocean: Their Ecology and Conservation*. (eds.) McClanahan T, Sheppard C and Obura D. Oxford University Press, Oxford, pp. 199–230.

Odum EP. 1962. Relationships between structure and function in the ecosystem. *Japanese Journal of Ecology* **12:** 108–118.

Odum EP. 1985. Trends expected in stressed ecosystems. *Bioscience.* **35(7):**419–422.

Ogden JC, Brown RA and Salesky N. 1973 Grazing by the echinoid *Diadema antillarum.* Formation of halos around West-Indian patch reefs. *Science* **182(7):** 715–717.

Ogden JC. 1980. *Faunal Relationships in Caribbean Seagrass Beds. In: Handbook of Seagrass Ecology*. (eds.) Phillips RC and McRoy CP. Garland STM Press.

Ojeda-Serrano E, Appeldoorn RS and Ruíz-Valentín I. 2007a. Reef fish spawning aggregations of the Puerto Rican shelf. *Proceedings of the Gulf and Caribbean Fisheries Institute* **59**: 467– 474.

Ojeda-Serrano E, Appeldoorn RS and Ruíz-Valentín I. 2007b. *Reef fish spawning aggregations of the Puerto Rican shelf*. Final report to the Caribbean Coral Reef Institute.

Oliver JK, Berkelmans R and Eakin CM. 2018. Coral bleaching in space and time. In: *Coral Bleaching*. Springer, Cham. pp. 27–49.

Oliver JK, King BA, Willis BL, Babcock RC and Wolanski E. 1992. Dispersal of coral larvae from a lagoonal reef—II. Comparisons between model predictions and observed concentrations. *Continental Shelf Research* **12(7–8)**:873–889.

Oliver L, Fisher W, Awkerman J, Campbell J, Harris P, Hemmer B, Lobue C, Parsons M, Santavy D and Vickery S. 2013. *Coral reef condition and benthic sedimentation threat in four regions of south Puerto Rico*. 22nd Biennial Conference of the Coastal and Estuarine Research Federation, November 3-7, 2013, San Diego, CA.

Oliver LM, Fisher WS, Dittmar J, Hallock P, Campbell J, Quarles RL, Harris P and LoBue C. 2014. Contrasting responses of coral reef fauna and foraminiferal assemblages to human influence in La Parguera, Puerto Rico. *Marine Environmental Resea*rch **99**: 95–105. doi:10.1016/j.marenvres.2014.04.005.

Oliver LM, Fisher WS, Fore L, Smith A and Bradley P. 2018. Assessing land use, sedimentation, and water quality stressors as predictors of coral reef condition in St. Thomas, U.S. Virgin Islands. *Environmental Monitoring and Assessment* **190**: 213–228.

Oliver LM, Lehrter JC, Fisher WS. 2011. Relating landscape development intensity to coral reef condition in the watersheds of St. Croix, US Virgin Islands. *Marine Ecology Progress Series* **427:** 293–302.

Oliver LM, Santavy DL, Bradley P. 2016. Developing a multi-stressor gradient model for coral reefs of Puerto Rico. *Proceedings of the 13th International Coral Reef Symposium, Honolulu*: 245–257.

Oliver TA and Palumbi SR. 2011. Do fluctuating temperature environments elevate coral thermal tolerance? *Coral Reefs* **30(2)**:429–40 doi:10.1007/s00338-011-0721-y.

Olsen DA and LaPlace JA. 1979. A study of a Virgin Islands grouper fishery based on a breeding aggregation. *Proceedings of the Gulf and Caribbean Fisheries Institute.* **31**:130–144.

Olsen DA, Dammann AE and LaPlace JA. 1978. Mesh selectivity of West Indian fish traps. *Marine Fisheries Review.* **40(7):**15–16.

Ormond RF, Roberts JM and Jan RQ. 1996. Behavioural differences in microhabitat use by damselfishes (*Pomacentridae*): implications for reef fish biodiversity. *Journal of Experimental Marine Biology and Ecology.* **202(1):**85–95.

Pandolfi JM and Jackson JBC. 2006. Ecological persistence interrupted in Caribbean coral reefs. *Ecology Letters* **9**:818–826.

Pandolfi JM, Bradbury RH, Sala E, Hughes TP, Bjorndal KA, Cooke RG, McArdle D, McClenachan L, Newman MJH, Paredes G, Warner RR and Jackson JBC. 2003. Global trajectories of the long-term decline of coral reef ecosystems. *Science* **301**: 955–958.

Pandolfi JM, Jackson JBC, Baron N and Bradbury RH. 2005. Are US coral reefs on the slippery slope to slime? *Science* **307**:1725−1726.

Pantos O, and Bythell JC. 2006. Bacterial community structure associated with white band disease in the elkhorn coral Acropora palmata determined using culture-independent 16S rRNA techniques. *Diseases of Aquatic Organisms* **69(1)**:79–88.

Pantos O, Cooney RP, Le Tissier MDA, Barer MR, O'Donnell AG, and Bythell JC. 2003. The bacterial ecology of a plague-like disease affecting the Caribbean coral *Montastrea annularis*. *Environmental Microbiology* **5(5):**370–382.

Pauly D, Christensen V, Dalsgaard J, Froese R and Torres F. 1998. Fishing down marine food webs. *Science.* **279(5352):**860–863.

Pauly D. 1995. Anecdotes and the shifting base-line syndrome of fisheries. *Trends in Ecology and Evolution* **10**: 430.

Pendleton LH. 1995. Valuing coral reef protection. *Ocean Coastal Management* **26**: 119–131.

Peters EC. 1997, Diseases of coral-reef organisms, chap. 6. In: *Life and death of coral reefs*. (ed) Birkeland, C. Chapman and Hall, New York. pp. 114–139.

Petes LE, Harvell CD, Peters EC, Webb MA and Mullen KM. 2003. Pathogens compromise reproduction and induce melanisation in Caribbean Sea fans. *Marine Ecology Progress Series.* **264:**167–171.

Pianka ER. 1970. On r-and K-selection. *The American Naturalist.* **104(940):**592–597.

Pinnegar JK, Polunin NV, Francour P, Badalamenti F, Chemello R, Harmelin-Vivien ML, Hereu B, Milazzo M, Zabala M, D'anna G and Pipitone C. 2000. Trophic cascades in benthic marine ecosystems: lessons for fisheries and protected-area management. *Environmental Conservation.* **1:**179–200.

Pittman SJ, 2017. *Seascape Ecology*. John Wiley & Sons. Hoboken, NJ, USA.

Pittman SJ, Christensen JD, Caldow C, Menza C and Monaco ME. 2007a. Predictive mapping of fish species richness across shallow-water seascapes in the Caribbean. *Ecological Modeling* **204**:9–21.

Pittman SJ, Hile SD, Jeffrey CFG, Clark R, Woody K, Herlach BD, Caldow C, Monaco ME and Appeldoorn R. 2010. *Coral reef ecosystems of Reserva Natural de La Parguera (Puerto Rico): Spatial and temporal patterns in fish and benthic communities (2001-2007)*. NOAA Technical Memorandum NOS NCCOS 107. NOS NCCOS CCMA Silver Spring, MD.

Pittman SJ, Kneib RT and Simenstad CA. 2011. Practicing coastal seascape ecology. *Marine Ecology Progress Series.* **427:**187–190.

Pittman, S.J., C. Caldow, S.D. Hile, and M.E. Monaco. 2007b. Using seascape types to explain the spatial patterns of fish in the mangroves of SW Puerto Rico. *Marine Ecology Progress Series* **348:**273–284.

Poff NL, Allan JD, Bain MB, Karr JR, Prestegaard KL, Richter BD, Sparks RE and Stromberg JC. 1997. The Natural Flow Regime. *BioScience* **47 (11)**:769–784.

Prada C, Weil E and Yoshioka PM. 2010. Octocoral bleaching during unusual thermal stress. *Coral Reefs* **29:** 41–45. doi:10.1007/s00338-009-0547-z.

Pratchett MS, Munday PL, Wilson SK, Graham NAJ, Cinner JE, Bellwood DR, Jones GP, Polunin NVC and McClanahan TR.2008. Effects of climate-induced coral bleaching on coral-reef fishes – Ecological and Economical Consequences. *Oceanographic and Marine Biology Annual Review* **46:**251–296.

Pratchett MS, Wilson SK and Baird AH. 2006. Declines in the abundance of *Chaetodon* butterflyfishes following extensive coral depletion. *Journal of Fish Biology* **69:** 1269–1280.

Precht WF, Gintert BE, Robbart ML, Fura R and van Woesik R. 2016. Unprecedented disease-related coral mortality in southeastern Florida: *Scientific Reports* **6**:31374.

Precht, W., Aronson R., Deslarzes K., Robbart M., Evans D., Zimmer B., and Duncan L. 2001. *Long-Term Monitoring at the East and West Flower Garden Banks, 2004-2005- Interim Report: Technical Report*. U. S. Department of the Interior, Minerals Management Service Gulf of Mexico OCS Regional Office New Orleans LA USA.

Principe P, Bradley P, Yee S, Fisher W, Johnson E, Allen P and Campbell D. 2012. *Quantifying Coral Reef Ecosystem Services.* U.S. Environmental Protection Agency, Office of Research and Development, Research Triangle Park, NC. EPA/600/R-11/206.

Purkis S and Kohler K. 2008. The role of topography in promoting fractal patchiness in a carbonate shelf landscape. *Coral Reefs* **27:**977–989.

Quigley KM, Strader ME and Matz MV. 2018. Relationship between *Acropora millepora* juvenile fluorescence and composition of newly established *Symbiodinium* assemblage. *PeerJ.* **6:**e5022.

Rachello-Dolmen PG and Cleary DF. 2007. Relating coral species traits to environmental conditions in the Jakarta Bay/Pulau Seribu reef system, Indonesia. *Estuarine, Coastal and Shelf Science.* **73(3–4):**816–826.

Ramos-Scharrón CE and Gilbes F. 2014. *Application of the Soil and Water Assessment Tool (SWAT) to estimate discharge and sediment yields from the Río Grande de Añasco watershed, Puerto Rico*. Final report to UPR-Sea Grant and Island Resources Foundation.

Randall CJ, Jordán-Garza AG, Muller EM and Van Woesik R. 2014. Relationships between the history of thermal stress and the relative risk of diseases of Caribbean corals. *Ecology.* **95(7):**1981–1994.

Randall JE. 1961. Tagging reef fishes in the Virgin Islands. *Proceedings of the Gulf and Caribbean Fisheries Institute* **14:**201–241.

Randall JE. 1963. An analysis of the reef fish populations of artificial and natural reefs in the Virgin Islands. *Caribbean Journal of Marine Science* **3:** 31–47.

Rapport DJ and Whitford WG. 1999. How ecosystems respond to stress: common properties of arid and aquatic systems. *BioScience.* **49(3):**193–203.

Raymundo LJ, Couch CS and Harvell CD (eds.). 2008. *Coral disease handbook—Guidelines for assessment, monitoring & management*. Queensland, Australia, The University of Queensland Coral Reef Targeted Research and Capacity Building for Management Program, 124 pp.

Recksiek CW, Murphy BR, Appeldoorn RS and Lindeman KC. 2001. Integrating fish fauna and habitat assessments: A fundamental step in developing fishery reserve design criteria. *Proceedings of the Gulf and Caribbean Fisheries Institute.* **52:**654–666.

Ricaurte M, Schizas NV, Ciborowski P and Boukli NM. 2016. Proteomic analysis of bleached and unbleached *Acropora palmata*, a threatened coral species of the Caribbean. *Marine Pollution Bulletin* **107(1)**:224–232.

Richmond RH, and Hunter CL. 1990. Reproduction and recruitment of corals: comparisons among the Caribbean, the Tropical Pacific, and the Red Sea. *Marine Ecology Progress Series* **60**:185–203.

Richmond RH. 1997. Reproduction and recruitment of corals: critical links in the persistence of reefs. In: *Life and Death of Coral Reefs* (ed.) Birkeland C. Chapman & Hall, New York, pp 175–197.

Risk MJ and Edinger E. 2011. Impacts of Sediment on Coral Reefs. In: *Encyclopedia of Modern Coral Reefs (ed.)* Hopley D. doi:10.1007/978-90-481-2639-2.

Risk MJ. 1972. Fish diversity on a coral reef in the Virgin Islands. *Atoll Research Bulletin* **152**:1–6.

Ritchie KB. 2006. Regulation of microbial populations by coral surface mucus and mucus-associated bacteria. *Marine Ecology Progress Series* **322:**1–4.

Roberts CM and Ormond RFG. 1987. Habitat complexity and coral reef fish diversity and abundance on Red Sea fringing reefs. *Marine Ecology Progress Series* **41**: 1–8.

Robertson DR, Sweatman HP, Fletcher EA and Cleland MG. 1976. Schooling as a mechanism for circumventing the territoriality of competitors. *Ecology.* **57(6):**1208–1220.

Robinson JPW, Williams ID, Edwards AM, McPherson J, Yeager L, Vigliola L and Baum JK. 2017. Fishing degrades size structure of coral reef fish communities. *Global Change Biology* **23(3):** 1009–1022.

Rocha LA, Pinheiro HT, Shepherd B, Papastamatiou YP, Luia OJ, Pyle RL and Bongaerts P. 2018. Mesophotic coral ecosystems are threatened and ecologically distinct from shallow water reefs. *Science* **361:** 281–284.

Roder C, Arif C, Daniels D, Weil E and Voolstra CR. 2014. Bacterial profiling of white plague disease across corals and oceans indicates a conserved and distinct disease microbiome. *Molecular Ecology* **23(4):**965–974.

Roff G, Doropoulos C, Rogers A, Bozec YM, Krueck NC, Aurellado E, Priest M, Birrell C and Mumby PJ. 2016. The ecological role of sharks on coral reefs. *Trends in Ecology and Evolution* **31:** 395–407.

Rogers CS and Garrison VH. 2001. Ten years after the crime—Lasting effects of damage from a cruise ship anchor on a coral reef in St. John, U.S. Virgin Islands. *Bulletin of Marine Science* **69(2):**793–803.

Rogers CS and Miller J. 2013. Coral diseases cause reef decline. *Science* **340(6140):**1522.

Rogers CS and Miller J. 2016. Measuring, interpreting, and responding to changes in coral reefs: A challenge for biologists, geologists, and managers. In: *Coral reefs at the crossroads*. Springer, Dordrecht. pp. 277–292

Rogers CS, and Miller J. 2013. Coral diseases cause reef decline. *Science* **340(6140)**:1522.

Rogers CS, and Muller EM. 2012. Bleaching, disease and recovery in the threatened scleractinian coral *Acropora palmata* in St. John, U.S. Virgin Islands—2003–2010. *Coral Reefs* **31**:807–819.

Rogers CS, Garrison G, Grober R, Hillis ZM and Franke MA. 1994. *Coral reef monitoring manual for the Caribbean and Western Atlantic*. U. S. National Park Service, St. John, U. S. Virgin Islands.

Rogers CS, Miller J, Muller EM, Edmunds P, Nemeth RS, Beets JP, Friedlander AM, Smith TB, Boulon R, Jeffrey CFG, Menza C, Caldow C, Idrisi N, Kojis B, Monaco ME, Spitzack A, Gladfelter EH, Ogden JC, Hillis-Starr Z, Lundgren I, Schill WB, Kuffner IB, Richardson LL, Devine BE, Voss JD. 2008. Ecology of coral reefs in the US Virgin Islands In: *Coral* R*eefs of the USA*. (eds) Riegl B, Dodge RE. Springer, Dordrecht, pp 303–374.

Rogers CS, Muller E, Spitzack A and Miller J. 2009. Extensive coral mortality in the US Virgin Islands in 2005/2006. A review of the evidence for synergy among thermal stress, coral bleaching and disease. *Caribbean Journal of Science* **45:**204–214.

Rogers CS. 1983. Sublethal and lethal effects of sediments applied to common Caribbean reef corals in the field. *Marine Pollution Bulletin* **14:**378–382.

Rogers CS. 1990. Responses of coral reefs and reef organisms to sedimentation. *Marine Ecology Progress Series* **62**:185–202.

Rogers CS. 2010. Words matter—Recommendations for clarifying coral disease nomenclature and terminology. *Diseases of Aquatic Organisms* **91(2):**167–175.

Rohmann SO, Hayes JJ, Newhall RC, Monaco ME and Grigg RW. 2005. The area of potential shallow-water tropical and subtropical coral ecosystems in the United States. *Coral Reefs.* **24(3):**370–383.

Rooker JR. 1995. Feeding ecology of the schoolmaster snapper, *Lutjanus apodus* (Walbaum), from southwestern Puerto Rico. *Bulletin of Marine Science.* **56(3):**881–894.

Rosenberg, E and Loya Y. 2004. Coral health and disease. Springer-Verlag KG, Berlin, Germany.

Rothenberger J, Blondeau J, Cox C, Curtis S, Fisher B, Garrison G, Hillis-Starr Z, Jeffrey C, Kadison E, Lundgren I, Miller W, Muller E, Nemeth RS, Paterson S, Rogers CS, Smith TB, Spitzack A, Taylor M, Toller W, Wright J and Wusinich-Mendez D. 2008. The State of

Coral Reef Ecosystems of the U.S. Virgin Islands. In: *The State of Coral Reef Ecosystems of the United States and Pacific Freely Associated States: 2008*. (eds.) Waddell JE, Clarke AM. NOAA Center for Coastal Monitoring and Assessment's Biogeography Team, Silver Spring, MD, p 567.

Rowan R and Knowlton N. 1995. Intraspecific diversity and ecological zonation in coral-algal symbiosis. *Proceedings of the National Academy of Sciences.* **92(7):**2850–2853.

Rowan R, Knowlton N, Baker A and Jara J. 1997. Landscape ecology of algal symbionts creates variation in episodes of coral bleaching. *Nature.* **88(6639):**265–269.

Rude J, Minks A, Doheny B, Tyner M, Maher K, Huffard C, Ismu Hidayat N and Grantham H. 2015. Ridge to reef modelling for use within land-sea planning under data-limited conditions*. Aquatic Conservation: Marine and Freshwater Ecosystems* **26(2):**251–64. doi: 10.1002/aqc.2548.

Ruiz-Moreno D, Willis BL, Page AC, Weil E, Cróquer A, Vargas-Angel B, Jordan-Garza AG, Jordán-Dahlgren E, Raymundo L, and Harvell CD. 2012. Global coral disease prevalence associated with sea temperature anomalies and local factors. *Diseases of Aquatic Organisms* **100**:249–261.

Russ G. 1985. Effects of protective management on coral reef fishes in the central Philippines. *In Proceedings of the fifth international coral reef congress*, Tahiti 1985 **4:**219–224.

Rutzler K, Santavy DL and Antonius A. 1983. The black band disease of Atlantic reef corals. *Marine Ecology.* **4(4):**329–358.

Ryan KE, Walsh JP, Corbett DR and Winter A. 2008. A record of recent change in terrestrial sedimentation in a coral-reef environment, La Parguera, Puerto Rico: A response to coastal development? *Marine Pollution Bulletin* **56:**1177–1183.

Sadovy Y and Eklund AM. 1999. *Synopsis of biological data on the Nassau grouper, Epinephelus striatus (Bloch, 1792), and the jewfish, E. itajara (Lichtenstein, 1822).* U.S. Department of Commerce. NOAA Technical Report NMFS 146, and FAO Fisheries Synopsis 157. Seattle, Washington, 65 pp.

Sadovy Y, Colin PL and Domeier ML. 1994a. Aggregation and spawning in the tiger grouper, *Mycteroperca tigris* (Pisces: Serranidae). *Copeia* **1994**: 511–516.

Sadovy Y, Rosario A and Román A. 1994b. Reproduction in an aggregating grouper, the red hind, *Epinephelus guttatus*. *Environmental Biology of Fishes* **41**:269–286.

Sala E, Ballesteros E and Starr RM. 2001. Rapid decline of Nassau grouper spawning aggregations in Belize: fishery management and conservation needs. *Fisheries* **26**:23–30.

Sale PF, Van Lavieren H, Ablan Lagman MC, Atema J, Butler M, Fauvelot C, Hogan JD, Jones GP, Lindeman KC, Paris CB, Steneck R and Stewart HL. 2010. *Preserving Reef Connectivity: A Handbook for Marine Protected Area Managers*. Connectivity Working Group, Coral Reef Targeted Research & Capacity Building for Management Program, UNU-INWEH.

Sale PF. 1991. Reef fish communities: open non-equilibrial systems. *The ecology of fishes on coral reefs.* 564–598.

Sammarco PW and Williams AH. 1982. Damselfish territoriality: Influence on Diadema distribution and implications for coral community structure. *Marine Ecology Progress Series.* Oldendorf. **8(1):**53–59.

Sanders RS, Miltner RJ, Yoder CO, and Rankin ET. 1999. The use of external deformities, erosions, lesions, and tumors (DELT anomalies) in fish assemblages for characterizing aquatic resources—A case study of seven Ohio streams. In: *Assessing the sustainability and biological integrity of water resources using fish communities*. (ed) Simon, TP. Boca Raton, Fla., CRC Press. pp. 225–248.

Sandin SA, Smith JE, DeMartini EE, Dinsdale EA, Donner SD, Friedlander AM, Konotchick T, Malay M, Maragos JE, Obura D and Pantos O. 2008. Baselines and degradation of coral reefs in the Northern Line Islands. *PloS one.* **3(2):**e1548.

Sano M, Shimizu M and Nose Y. 1984. Changes in structure of coral reef fish communities by destruction of hermatypic corals: observational and experimental views. *Pacific Science* **38:**51–79.

Sano M, Shimizu M, Nose Y. 1987. Long-term effects of destruction of hermatypic corals by *Acanthaster planci* infestation on reef fish communities at Iriomote Island, Japan. *Marine Ecology Progress Series* **37**:191–199.

Santavy DL, Bradley P, Gerritsen J and Oliver L. 2016. The Biological Condition Gradient, a Tool used for Describing the Condition of US Coral Reef Ecosystems. *Proceedings of the 13th International Coral Reef Symposium* 557–568.

Santavy DL, Fisher WS, Campbell JG and Quarles RL. 2012. *Field Manual for Coral Reef Assessments*. U.S. Environmental Protection Agency, Office of Research and Development, Gulf Ecology Division, Gulf Breeze, FL. EPA/600/R-12/029.

Santavy DL, Summers JK, Engle VD, and Harwell LC. 2005. The condition of coral reefs in South Florida (2000) using coral disease and bleaching as indicators. *Environmental Monitoring and Assessment* **100**:129–152.

Saunders DA, Hobbs RJ and Margules CR. 1991. Biological consequences of ecosystem fragmentation: a review. *Conservation biology.* **5(1):**18–32.

Schärer MT, Nemeth MI and Appeldoorn RS. 2010. Protecting a multi-species spawning aggregation at Mona Island, Puerto Rico. *In Proceedings of the Gulf and Caribbean Fisheries Institute* **62**:252–259.

Schärer MT, Nemeth MI, Appeldoorn RS. 2008. Mapping ontogenetic habitat shifts of coral reef fish at Mona Island, Puerto Rico. In: *Proceedings of the 60th Gulf and Caribbean Fisheries Institute* November 5–9, 2007 Punta Cana, Dominican Republic: 305–310.

Schärer MT, Nemeth MI, Appeldoorn RS. 2010. Protecting a multi-species spawning aggregation at Mona Island, Puerto Rico. In: *Proceedings of the Gulf and Caribbean Fisheries Institute* **62**:52–259.

Schärer MT, Nemeth MI, Rowell TJ and Appeldoorn RS. 2014. Sounds associated with the reproductive behavior of the black grouper (*Mycteroperca bonaci*). *Marine biology.* **161(1):**141–147.

Schärer-Umpierre MT. 2009. *Using landscape ecology to describe habitat connectivity for coral reef fishes*. PhD Thesis, University of Puerto Rico. Mayagüez, Puerto Rico, 216 pp.

Scherbina AY, Gawarkiewicz GG, Linder CA and Thorrold SR. 2008. Mapping bathymetric and hydrographic features of Glover's Reef, Belize, with a REmuS autonomous underwater vehicle. *Limnology and Oceanography* **53**: 2264–2272.

Sekar R, Mills DK, Remily ER, Voss JD, and Richardson LL. 2006. Microbial communities in the surface mucopolysaccharide layer and the black band microbial mat of black band-diseased *Siderastrea siderea*. *Applied and Environmental Microbiology* **72(9)**:5963–5973.

Shapiro DY, Sadovy Y and McGehee MA. 1993. Size, composition, and spatial structure of the annual spawning aggregation of the Red hind, *Epinephelus guttatus* (Pisces: Serranidae). *Copeia* **1993**: 399–406.

Sheaves M. 2009. Consequences of ecological connectivity: the coastal ecosystem mosaic. *Marine Ecology Progress Series.* **391***:*107–115.

Shepherd AR, Warwick RM, Clarke KR and Brown BE.1992. An analysis of fish community responses to coral mining in the Maldives. *Environmental Biology of Fishes.* **33(4):**367.

Sheppard C, Teleki K and Turner J. 2000. Measuring change and recovery in reef ecosystems. *Coral reef degradation in the Indian Ocean*.

Shumchenia EJ, Guarinello ML and King JW. 2016. A re-assessment of Narragansett Bay benthic habitat quality between 1988 and 2008. *Estuaries and Coasts.* ***39*****(5)**:1463–1477.

Simon TP. (ed). 2003. *Biological response signatures—Indicator patterns using aquatic communities*. Boca Raton, FL, CRC Press, 576 pp.

Skirving, WJ, Heron SF, Marsh BL, Liu G, De La Cour JL, Geiger EF, and Eakin CM. 2019. The relentless march of mass coral bleaching—A global perspective of changing heat stress. *Coral Reefs* **38**:547–557.

Smith CL. 1972. Space resource sharing in a coral reef fish community. *Bulletin of Natural History Museum Los Angeles City.* **14:**125–170.

Smith L, Devlin M, Haynes D and Gilmour J. 2005. A demographic approach to monitoring the health of coral reefs. *Marine Pollution Bulletin* **51:** 399–407.

Smith SG, Ault JS, Bohnsack JA, Harper DE, Luo J and McClellan DB. 2011. Multispecies survey design for assessing reef-fish stocks, spatially-explicit management performance, and ecosystem condition. *Fisheries Research* **109**: 25–41.

Smith TB, Blondeau J, Nemeth RS, Pittman SJ, Calnan JM, Kadison E and Gass J. 2010. Benthic structure and cryptic mortality in a Caribbean mesophotic coral reef bank system, the Hind Bank Marine Conservation District, U.S. Virgin Islands. *Coral Reefs* **29:**289–308.

Smith TB, Ennis RS, Kadison E, Weinstein DW, Jossart J, Gyory J and Henderson L. 2015. *The United States Virgin Islands Territorial Coral Reef Monitoring Program. Year 2015 Annual Report*. **1**:288.

Smith TB, Nemeth RS, Blondeau J, Calnan JM, Kadison E and Herzlieb S. 2008. Assessing coral reef health across onshore to offshore stress gradients. *Marine Pollution Bulletin* **56**:1983–1991.

Soffer N, Brandt ME, Correa AM, Smith TB and Thurber RV. 2014. Potential role of viruses in white plague coral disease. *The ISME Journal* **8(2):**271–283.

Solano M, Canals M and Leonardi S, 2018. Development and validation of a coastal ocean forecasting system for Puerto Rico and the U.S. Virgin Islands. *Journal of Ocean Engineering and Science* **3:** 223–236.

Soong K. 1991. Sexual reproductive patterns of shallow-water reef corals in Panama. *Bulletin of marine science.* **49(3):**832–846.

Soong K. 1993. Colony size as a species character in massive reef corals. *Coral reefs.* **12(2):**77–83.

Spalding M, Burke L, Wood SA, Ashpole J, Hutchison J and Ermgassen P. 2017. Mapping the global value and distribution of coral reef tourism. *Marine Policy* **82**:104–113.

Spalding MD and Jarvis GE. 2002. The impact of the 1998 coral mortality on reef fish communities in the Seychelles. *Marine Pollution Bulletin.* **44(4):**309–321.

Stafford-Smith MG and Ormond RF. 1992. Sediment-rejection mechanisms of 42 species of Australian scleractinian corals. *Marine and Freshwater Research.* **43(4):**683–705.

Stallings CD. 2008. Indirect effects of an exploited predator on recruitment of coral-reef fishes. *Ecology* **89**:2090–2095.

Stallings CD. 2009. Predator identity and recruitment of coral-reef fishes: indirect effects of fishing. *Marine Ecology Progress Series* **383**:251–259.

Stearns SC. 1977. The evolution of life history traits: a critique of the theory and a review of the data. *Annual review of ecology and systematics.* **8(1):**145–171.

Stedman TL. 2006. Stedman's Medical Dictionary (27th ed.). Baltimore, Md., Lippincott Williams & Wilkins, 2,098 pp.

Steneck RS, Paris CB, Arnold SN, Ablan-Lagman MC, Alcala AC, Butler MJ, McCook LJ, Russ GR and Sale PF. 2009. Thinking and managing outside the box: coalescing connectivity networks to build region-wide resilience in coral reef ecosystems. *Coral Reefs.* **28(2):**367–378.

Steneck RS, Vavrinec J and Leland AV. 2004 Trophic-Level Dysfunction in Kelp Forest Ecosystems of the Western North Atlantic. *Ecosystems* **7**:523–552.

Stevens DL Jr. and Olsen AR. 2004. Spatially Balanced Sampling of Natural Resources. *Journal of the American Statistical Association* **99(465):** 262–277.

Stoddard JL, Larsen DP, Hawkins CP, Johnson RK, and Norris RH. 2006. Setting expectations for the ecological condition of streams: The concept of reference condition. *Ecological Applications* **16**: 1267–1276.

Stoddart DR. 1972. Catastrophic damage to coral reef communities by earthquake. *Nature* **239(5366)**:51–52.

Storlazzi CD, Dartnell P, Hatcher GA and Gibbs AE. 2016. End of the chain? Rugosity and fine-scale bathymetry from existing underwater digital imagery using structure-from-motion (SfM) technology. *Coral Reefs* **35:**889–894.

Strong AE, Liu G, Skirving W and Eakin CM. 2011. NOAA's Coral Reef Watch program from satellite observations. *Annals* of *GIS* **17:**83–92. doi: 10.1080/19475683.2011.576266

Sunagawa S, DeSantis TZ, Piceno YM, Brodie EL, DeSalvo MK, Voolstra CR, Weil E, Andersen GL, and Medina M. 2009. Bacterial diversity and white plague disease-associated community changes in the Caribbean coral *Montastraea faveolata*. *The ISME Journal* **3**:512–521.

Sutherland KP, Berry B, Park A, Kemp DW, Kemp KM, Lipp EK and Porter JW. 2016, Shifting white pox aetiologies affecting *Acropora palmata* in the Florida Keys, 1994–2014. *Philosophical Transactions of the Royal Society B Biological Sciences* **371(1689)**:20150205.

Sutherland KP, Porter JW and Torres C. 2004. Disease and immunity in Caribbean and Indo-Pacific zooxanthellate corals. *Marine Ecology Progress Series* **266**:273–302.

Sutherland KP, Porter JW, Turner JW, Thomas BJ, Looney EE, Luna TP, Meyers MK, Futch JC and Lipp EK. 2010. Human sewage identified as likely source of white pox disease of the threatened Caribbean elkhorn coral, *Acropora palmata*. *Environmental Microbiology* **12(5):**1122–1131.

Sweet MJ and Séré MG. 2015. Ciliate communities consistently associated with coral diseases. *Journal of Sea Research* **113:**119–131.

Syms C and Jones GP. 2000. Disturbance, habitat structure, and the dynamics of a coral-reef fish community. *Ecology.* **81(10):**2714–2729.

Szmant A and Gassman NJ. 1990. The effects of prolonged "bleaching" on the tissue biomass and reproduction of the reef coral *Montastrea annularis*. *Coral Reefs* **8(4):**217–224.

Szmant AM, Weil E, Miller MW and Colon DE. 1997. Hybridization within the species complex of the scleractinan coral *Montastraea annularis*. *Marine Biology.* **129(4):**561–572.

Szmant AM. 1986. Reproductive ecology of Caribbean reef corals. *Coral Reefs* **5(1):**43–53.

Talbot FH and Goldman B. 1972. A preliminary report on the diversity and feeding relationships of reef fishes of One Tree Island, Great Barrier Reef system. *Proceedings of the First International Symposium on Corals and Coral Reefs* **1**:425–443.

Talbot FH. 1965. A Description of The Coral Structure of Tutia Reef (Tanganyika Territory, East Africa), and its Fish Fauna. *Proceedings of the Zoological Society of London* **145:**431–470.

Teixeira H, Borja A, Weisberg SB, Ranasinghe JA, Cadien DB, Dauer DM, Dauvin J, Degraer S, Diaz RJ, Grémare A, Karakassis I, Llansó RJ, Lovell LL, Marques JC, Montagne DE, Occhipinti-Ambrogi A, Rosenberg R, Sardá R, Schaffner LC, and Velarde RG. 2010. Assessing coastal benthic macrofauna community condition using best professional judgement—developing consensus across North America and Europe. *Marine Pollution Bulletin* **60**:589–600.

Tetra Tech. 2020 (unpublished memo). *Comparison of Coral Reef Monitoring Protocols in the Caribbean*. Prepared by Tetra Tech, Fairfax, VA. Prepared for U.S. EPA.

Thompson R and Munro JL. 1974. *The biology, ecology and exploitation and management of the Caribbean reef fishes. Part V. Carangidae (jacks)*. Research report from the Zoology Department, University of the West Indies.

Thornhill DJ, Fitt WK and Schmidt GW. 2006. Highly stable symbioses among western Atlantic brooding corals. *Coral Reefs.* **25(4):**515–519.

Thornhill DJ, LaJeunesse TC, Kemp DW, Fitt WK and Schmidt GW. 2006. Multi-year, seasonal genotypic surveys of coral-algal symbioses reveal prevalent stability or post-bleaching reversion. *Marine Biology.* **148(4):**711–722.

Thornhill DJ, Lewis AM, Wham DC and LaJeunesse TC. 2014. Host-specialist lineages dominate the adaptive radiation of reef coral endosymbionts. *Evolution* **68(2):**352–367.

Toller WW, Rowan R and Knowlton N. 2001a. Zooxanthellae of the Montastraea annularis species complex: patterns of distribution of four taxa of Symbiodinium on different reefs and across depths. *The Biological Bulletin.* **201(3):**348–59.

Toller WW, Rowan R and Knowlton N. 2001b. Repopulation of zooxanthellae in the Caribbean corals *Montastraea annularis* and *M. faveolata* following experimental and disease-associated bleaching. *The Biological Bulletin.* **201(3):**360–73.

Tomascik I and Sander F. 1985. Effects of eutrophication on reef-building corals. II. Structure of scleractinian coral communities on fringing reefs, Barbados, West Indies. *Marine Biology* **94:**53–75.

Tracy AM, Koren O, Douglas N, Weil E, Harvell CD. 2015. Persistent shifts in Caribbean coral microbiota are linked to the 2010 warm thermal anomaly. *Environmental Microbiology Reports* **7(3)**:471–479.

Tsounis G and Edmunds PJ. 2017. Three decades of coral reef community dynamics in St. John, USVI: a contrast of scleractinians and octocorals. *Ecosphere* **8(1)**:e01646.

Tuohy E, Wade C and Weil E. 2020. Lack of recovery of the long-spined sea urchin *Diadema antillarum Philippi* in Puerto Rico 33 years after the Caribbean-wide mass mortality. *PeerJ.* **12:8:**e8428.

Turner MG and Gardner RH. 1991. Quantitative methods in landscape ecology: an introduction. *Ecological studies*. **82:**3–14.

Turner MG, Gardner RH and O'Neill RV. 2001. *Landscape ecology in theory and practice.* Springer-Verlag, New York.

U.S. Coast Guard. 2019. Ballast Water Best Management Practices to Reduce the Likelihood of Transporting Pathogens That May Spread Stony Coral Tissue Loss Disease. *Marine Safety Information Bulletin*. Washington, DC.

U.S. Environmental Protection Agency (EPA). 2002. *Biological Assessments and Criteria: Crucial Components of Water Quality Programs*. EPA-822-F-02-006.

U.S. Environmental Protection Agency (EPA). 2013. *Biological Assessment Program Review: Assessing Level of Technical Rigor to Support Water Quality Management*. EPA 820-R-13-001. U.S. Environmental Protection Agency, Washington, DC.

U.S. Environmental Protection Agency (EPA). 2016. *A Practitioner's Guide to the Biological Condition Gradient: A Framework to Describe Incremental Change in Aquatic Ecosystems*. EPA 842-R-16-001. Wash. DC.

United Nations Environment Programme-World Conservation Monitoring Centre (UN-WCMC) 2006. *In the front line: shoreline protection and other ecosystem services from mangroves and coral reefs.* UNEP-WCMC, Cambridge, UK 33 pp.

Urban DL, O'Neill RV and Shugart HH. 1987. Landscape ecology: A hierarchical perspective can help scientists understand spatial patterns. *BioScience.* **37:**119–127.

Van Hooidonk R, Maynard J, Tamelander J, Gove J, Ahmadia G, Raymundo L, Williams G, Heron SF and Planes S. 2016. Local-scale projections of coral reef futures and implications of the Paris Agreement. *Scientific reports.* **6(1):**1–8.

Van Oppen MJ and Lough JM. 2018. Synthesis: Coral bleaching: Patterns, processes, causes and consequences. In: *Coral bleaching*. Springer, Cham. pp. 343–348

Van Oppen MJ, Bongaerts P, Frade P, Peplow LM, Boyd SE, Nim HT and Bay LK. 2018. Adaptation to reef habitats through selection on the coral animal and its associated microbiome. *Molecular ecology.* **27(14):**2956–2971.

Van Oppen MJ, Willis BL, Van Rheede T and Miller DJ. 2002. Spawning times, reproductive compatibilities and genetic structuring in the Acropora aspera group: evidence for natural hybridization and semi-permeable species boundaries in corals. *Molecular Ecology.* **11(8):**1363–1376.

van Woesik R, Franklin EC, O'Leary J, McClanahan T, Klaus JS and Budd AF. 2012. Hosts of the Plio-Pleistocene past reflect modern-day coral vulnerability. *Proceedings of the Royal Society B* **279(1737):**2448–2456.

Vega Thurber RL and Correa AM. 2011. Viruses of reef-building scleractinian corals. *Journal of Experimental Marine Biology and Ecology.* **408(1-2):**102–113.

Vega Thurber RL, Barott KL, Hall D, Liu H, Rodriguez-Mueller B, Desnues C, Edwards RA, Haynes M, Angly FE, Wegley L and Rohwer FL. 2008. Metagenomic analysis indicates that stressors induce production of herpes-like viruses in the coral *Porites compressa*. *Proceedings of the National Academy of Sciences.* **105(47):**18413–18418.

Vega Thurber RL, Burkepile DE, Fuchs C, Schantz AA, McMinds R and Zanzeveld JR. 2014. Chronic nutrient enrichment increases prevalence and severity of coral disease and bleaching. *Global Change Biology* **20**:544–554.

Vega Thurber RV, Willner-Hall D, Rodriguez-Mueller B, Desnues C, Edwards RA, Angly F, Dinsdale E, Kelly L and Rohwer F. 2009. Metagenomic analysis of stressed coral holobionts. *Environmental Microbiology* **11(8):**2148–2163.

Vermeij MJ. 2006. Early life-history dynamics of Caribbean coral species on artificial substratum: the importance of competition, growth and variation in life-history strategy. *Coral Reefs.* **25(1):**59–71.

Vermeij MJ.2005. Substrate composition and adult distribution determine recruitment patterns in a Caribbean brooding coral. *Marine Ecology Progress Series.* **23(295):**123–133.

Vermeij MJA, Sampayo E, Bröker K and Bak RPM. 2003. Differences in reproductive behavior of closely related Madracis species: Larval release and early life history processes. *Marine Ecology Progress Series* **297:** 75–84.

Veron JN. 2000. *Corals of the World* Vols 1–3. Australan Institute of Marine Science.

Verweij MC, Nagelkerken I, De Graaff D, Peeters M, Bakker EJ and Van der Velde G. 2006. Structure, food and shade attract juvenile coral reef fish to mangrove and seagrass habitats: a field experiment. *Marine Ecology Progress Series.* **306:**257–268.

Vollmer SV and Palumbi SR. 2002. Hybridization and the evolution of reef coral diversity. *Science.* **296(5575):**2023–2025.

Walker BK, Jordan LKB and Spieler RE. 2009. Relationship of Reef Fish Assemblages and Topographic Complexity on Southeastern Florida Coral Reef Habitats. *Journal of Coastal Research* **53**:39–48.

Wallace CC. 1999. Staghorn Corals of the World: A Revision of the Genus Acropora. CSIRO Publishing, Melbourne, Australia. p. 421.

Walton CJ, Hayes NK and Gilliam DS. 2018. Impacts of a regional, multi-year, multi-species coral disease outbreak in Southeast Florida. *Frontiers in Marine Science.* **5:**323.

Ward-Paige CA, Mora C, Lotze HK, Pattengill-Semmens C, McClenachan L, Arias-Castro E and Myers RA. Large-scale absence of sharks on reefs in the greater-Caribbean: a footprint of human pressures. *PloS one.* **5(8):**e11968.

Warren-Rhodes K, Sadovy Y and Cesar H. 2003. Marine ecosystem appropriation in the Indo-Pacific: A case study of the live reef fish food trade. *Ambio: A Journal of the Human Environment.* **32(7):**481–488.

Weber M, De Beer D, Lott C, Polerecky L, Kohls K, Abed RM, Ferdelman TG and Fabricius KE. 2012. Mechanisms of damage to corals exposed to sedimentation. *Proceedings of the National Academy of Sciences.* **109(24):**E1558–1567.

Weiblen GD, Oyama RK and Donoghue MJ. 2000. Phylogenetic analysis of dioecy in monocotyledons. *American Naturalist.* **155:**46–58.

Weil E and Rogers CS. 2011. Coral Reef disease in the Atlantic-Caribbean. In *Coral Reefs: An Ecosystem in Transition* Chapter 27. Z. (eds.) Dubinski and Stambler N. Springer-Verlag. pp. 465–492.

Weil E, and Hooten A. 2008. Underwater cards for assessing coral health on Caribbean reefs, Global Environment Facility-Coral Reef Targeted Research Program resource. Brisbane, Australia, Center for Marine Sciences, University of Queensland, 24 pp.

Weil E, Cróquer A, and Urreiztieta I. 2009a. Temporal variability and impact of coral diseases and bleaching in La Parguera, Puerto Rico from 2003–2007. *Caribbean Journal of Science* **45(2–3)**:221–246.

Weil E, Cróquer A, and Urreiztieta I. 2009b. Yellow band disease compromises the reproductive output of the reef-building coral *Montastraea faveolata* (Anthozoa, Scleractinia). *Diseases of Aquatic Organisms* **87(1–2)**:45–55.

Weil E, Hernandez EA, Bruckner AW, Ortiz AL, Nemeth M and Ruiz H, 2002. Distribution and status of acroporid (scleractinia) coral populations in Puerto Rico. *Proceedings of the Caribbean Workshop: Potential Application of the US Endangered Species Act (ESA) as a Conservation Strategy*. NOAA-NMFS and NCORE – RSMAS. U. of Miami. April 16 - 18. pp. 71-92**.**

Weil E, Hernandez-Delgado H, Gonzalez M, Williams S, Suleiman-Ramos S, Figuerola M and Metz-Estrella T. 2019. Spread of the new coral disease "SCTLD" into the Caribbean—Implications for Puerto Rico. *Reef Encounter* **34(1):**38–43.

Weil E, Rogers C, and Cróquer A. 2017. Octocoral diseases in a changing sea, In: *Marine animal forests—The ecology of benthic biodiversity hotspots*. (eds) Rossi, S., Gori, A., Orejas Seco del Valle, C. Champaign, Ill., Springer, pp. 1–55.

Weil E, Smith G and Gil-Agudelo DL. 2006. Status and progress in coral reef disease research. *Diseases of aquatic organisms.* **69(1):**1–7.

Weil E, Torres JL and Ashton M. 2005. Population characteristics of the sea urchin *Diadema antillarum* in La Parguera, Puerto Rico, 17 years after the mass mortality event. *Revista de biología tropical.* **53(3):**219–231.

Weil E, Urreiztieta I and Garzón-Ferreira J. 2002. Geographic variability in the incidence of coral and octocoral diseases in the wider Caribbean. In: *International Coral Reef Symposium, Bali, Indonesia, 9th, October 23–27, 2000, Proceedings*. Bali, Indonesia, International Coral Reef Society, p. 1231–1237.

Weil E. 2003. The corals and coral reefs of Venezuela. In Latin American coral reefs. *Elsevier Science.* 303–330.

Weil E. 2004. Coral reef diseases in the wider Caribbean. In: *Coral health and disease*. (eds) Rosenberg, E., and Loya, Y. Heidelberg, Germany, Springer, pp. 35–68.

Weil E. 2019 *Metadata for Caribbean Coral Species*. Prepared for US EPA (Appendix S of this report).

Weil E. 2020 *Characterization of BCG Condition Level 1 for coral reefs in Puerto Rico and the US Virgin Islands*. Prepared for US EPA (Appendix L of this publication).

Weisberg SB, Thompson B, Ranasinghe JA, Montagne DE, Cadien DB, Dauer DM, Diener D, Oliver J, Reish DJ, Velarde RG and Word JQ. 2008. The level of agreement among experts applying best professional judgment to assess the condition of benthic infaunal communities. *Ecological Indicators* **8**:389–394.

Wells JW. 1954. Recent corals of the Marshall Islands. *U.S. Geological Survey Professional Paper*. **260(1)**:285–486

Wenger AS, Fabricius KE, Jones GP and Brodie JE. 2015. Effects of sedimentation, eutrophication, and chemical pollution on coral reef fishes, Chap 15. In: *Ecology of fishes on coral reefs*. (ed.) Mora C. Cambridge University Press, Cambridge, pp. 145−153.

Weynberg KD, Laffy PW, Wood-Charlson EM, Turaev D, Rattei T, Webster NS and Van Oppen MJ. 2017. Coral-associated viral communities show high levels of diversity and host auxiliary functions. *PeerJ.* **5:**e4054.

Whaylen L, Pattengill-Semmens CV, Semmens BX, Bush PG and Boardman MR. 2004. Observations of a Nassau grouper, Epinephelus striatus, spawning aggregation site in Little Cayman, Cayman Islands, including multi-species spawning information. *Environmental Biology of Fishes.* **70(3):**305–313.

Wiens JA and Moss MR. 2005. Issues and perspectives in landscape ecology. *Cambridge University Press.* Cambridge

Wiens JA, Crawford CS and Gosz JR. 1985. Boundary dynamics: a conceptual framework for studying landscape ecosystems. *Oikos.* **1:**421–427.

Wiens JA, Milne BT. 1989. Scaling of 'landscapes' in landscape ecology, or, landscape ecology from a beetle's perspective. *Landscape ecology*. **3(2)**:87–96.

Wiens JA. 1992. What is landscape ecology, really? *Landscape Ecology.* **7:**149–150.

Wilkinson C, Souter D and Goldberg J. 2005. *Status of coral reefs in tsunami-affected countries: 2005*. Australian Institute of Marine Science. Global Coral Reef Monitoring Network. Townsville, AUS.

Wilkinson C. 2008. *Status of Coral Reefs of the World: 2008*. Global Coral Reef Monitoring Network. Townsville, AUS.

Wilkinson CR and Souter D. 2008. *Status of Caribbean Coral Reefs After Bleaching and Hurricanes in 2005.* Global Coral Reef Monitoring Network, and Reef and Rainforest Research Centre, Townsville, AUS.

Wilkinson, C. 2004. *Status of coral reefs of the world: 2004*. Australian Institute of Marine Science, Townsville, AUS.

Williams DM. 1991. Patterns and processes in the distribution of coral reef fishes. In: *The ecology of fishes on coral reefs*. (ed.) Sale, PF. Academic Press, San Diego, pp. 437–474

Williams EH Jr, Bartels PJ and Bunkley-Williams L. 1999. Predicted disappearance of coral-reef ramparts: A direct result of major ecological disturbances. *Global Change Biology* **5:**1–7.

Williams I and Polunin N. 2001. Large-scale associations between macroalgal cover and grazer biomass on mid-depth reefs in the Caribbean. *Coral reefs.* **19(4):**358–366.

Williams SM, Mumby PJ, Chollett I and Cortes J. 2015. Importance of differentiating Orbicella reefs from gorgonian plains for ecological assessments of Caribbean reefs. *Ma*rine *Eco*logy *Prog*ress *Ser*ies **530**:93–101.

Willis BL, Babcock RC, Harrison PL and Wallace CC. 1997. Experimental hybridization and breeding incompatibilities within the mating systems of mass spawning reef corals. *Coral Reefs.* **16(1):**S53–65.

Wilson WH, Francis I, Ryan K and Davy SK. 2001. Temperature induction of viruses in symbiotic dinoflagellates. *Aquatic Microbial Ecology.* **25(1):**99–102.

Wilson SK, Graham NAJ, Pratchett MS, Jones GP, and Polunin NVC.. 2006. Multiple disturbances and the global degradation of coral reefs: are reef fishes at risk or resilient? *Global Change Biology* **12:**2220–2234.

Woodley CM, Downs CA, Bruckner AW, Porter JW, Galloway S. 2016. *Diseases of coral*. John Wiley & Sons. Hoboken, NJ.

Wooldridge SA, and Done TJ. 2009. Improved water quality can ameliorate effects of climate change on corals. *Ecological Applications* **19(6)**:1492–1499.

Work TM and Aeby GS. 2006. Systematically describing gross lesions in corals. *Diseases of Aquatic Organisms* **70(1–2):**155–160.

World Resources Institute (WRI). 2009. Value of Coral Reefs & Mangroves in the Caribbean. *Economic Valuation Methodology* V3.0.

Yee SH, Carriger JF, Bradley P, Fisher WS and Dyson B. 2015. Developing scientific information to support decisions for sustainable coral reef ecosystem services. *Ecological Economics* **115:**39–50.

Yee SH, Kern JW, Santavy D, and Hession D. 2011. Consideration of species community composition in statistical analyses of coral disease risk. *Marine Ecology Progress Series* **431**:83–96.

Yoder CO and Rankin ET. 1995. Biological response signatures and the area of degradation value—New tools for interpreting multimetric data. In: *Biological assessment and criteria—Tools for water resource planning and decision making*. (eds.) Davis WS and Simon TP. Boca Raton, Fla., Lewis Publishers, p. 263–286.

Yonge CM and Nichols AG. 1931. Studies on the physiology of corals: V. The effect of starvation in light and in darkness on the relationship between corals and zooxanthellae. *Scientific Reports/Great Barrier Reef Expedit*ion **1:**177–211.

Yonge, CM. 1930. Studies on the physiology of corals. I. Feeding mechanisms and food. *Scientific Report of the Great Barrier Reef Expedition* **1(2)**:13–57.

Zadeh LA. 2008. Is there a need for fuzzy logic? *Information Sciences* **178:**2751–2799.

Zitello AG, Bauer LJ, Battista TA, Mueller PW, Kendall MS and Monaco ME. 2009. *Shallow-Water Benthic Habitats of St. John, U.S. Virgin Islands*. NOAA Technical Memorandum NOS NCCOS 96. Silver Spring, MD.

Appendices

Appendix A – Glossary

abundance: An ecological concept referring to the relative representation of a species in a particular ecosystem.

anthropogenic: Originating from man, not naturally occurring.

assemblage: An association of interacting populations of organisms in a given waterbody.

arthropod: An invertebrate animal having an exoskeleton (external skeleton), a segmented body, and jointed appendages (paired appendages).

attribute: Any measurable component of a biological system (Karr and Chu 1999). The BCG describes how ten biological attributes of natural aquatic systems change in response to increasing pollution and disturbance. The ten BCG attributes are in principle measurable, although several are not commonly measured in monitoring programs. The BCG attributes are:

- Historically documented, sensitive, long-lived or regionally endemic taxa
- Sensitive and rare taxa
- Sensitive but ubiquitous taxa
- Taxa of intermediate tolerance
- Tolerant taxa
- Non-native taxa
- Organism condition
- Ecosystem functions
- Spatial and temporal extent of detrimental effects
- Ecosystem connectivity

bait species: Small fish caught for use as bait to attract larger predatory fish, particularly game fish.

benthic: Living in or on the bottom of a body of water.

best attainable condition: A condition that is equivalent to the ecological condition of (hypothetical) least disturbed sites where the best possible management practices are in use. This condition can be determined using techniques such as historical reconstruction, best ecological judgment and modeling, restoration experiments, or inference from data distributions.

Biological Condition Gradient (BCG): A scientific model that describes how biological attributes of aquatic ecosystems (i.e., biological condition) might change along a gradient of increasing anthropogenic stress.

biological criteria: Narrative expressions or numerical values that define an expected or desired biological condition for a waterbody and can be used to evaluate the biological integrity of the waterbody. When adopted by the U.S. jurisdictions, they become legally enforceable standards.

biological integrity: The capacity of supporting and maintaining a balanced, integrated, adaptive community of organisms having a species composition, diversity, and functional organization comparable to that of the natural habitat of the region.

biological traits: A specific characteristic of an organism (e.g., life stage, body size, life history, physiology and behavior) that reflect both inter-specific interactions and the connection between species and their environment.

calcareous reef: Reefs formed as calcareous (calcium carbonate) skeletons are deposited and bound by corals.

carbon dioxide (CO2): A heavy odorless colorless gas formed during respiration and by the decomposition of organic substances; absorbed from the air by plants in photosynthesis. It is also a by-product of burning fossil fuels and biomass, as well as land-use changes and other industrial processes. It is the principal anthropogenic greenhouse gas affecting the Earth's radiative balance.

carnivore: Meaning 'meat eater' is an organism that derives its energy and nutrient requirements from a diet consisting mainly or exclusively of animal tissue, whether through predation or scavenging.

Clean Water Act (CWA): An act passed by the U.S. Congress to control water pollution (also known as the Federal Water Pollution Control Act (33 U.S.C. 1251 et seq.) [As Amended Through P.L. 107–303, November 27, 2002] (Bradley et al. 2010).

community: All the groups of organisms living together in the same area, usually interacting or depending on each other for existence (Bradley et al. 2010).

condition: The relative ability of an aquatic resource to support and maintain a community of organisms having a species composition, diversity, and functional organization comparable to reference aquatic resources in the region.

connectivity: The demographic linking of local populations through dispersal of pelagic larvae and movement of juveniles or adults (Jones et al. 2009). There are different types of connectivity including: connectivity among populations in the same habitat in different locations; connectivity among marine habitats (e.g., where species use different habitats at different stages in their life history); and connectivity between the land and the sea.

coral bleaching: When corals are stressed by changes in conditions such as temperature, light, or nutrients, they expel the symbiotic algae living in their tissues, causing them to turn completely white.

coral reef: Any reefs or shoals composed primarily of corals and formed by coral growth.

decision rules: Logic statements that experts use to make their decisions.

diversity: in relation to species, the number of species and abundance of each species that live in a particular location

echinoderm: Any of various marine invertebrates of the phylum Echinodermata, having a lattice like internal skeleton composed of calcite and usually a hard, spiny outer covering. The body plans of adult echinoderms show radial symmetry, typically in the pattern of a five-pointed star, while the larvae show bilateral symmetry. Examples are starfish, sea urchin, or sea cucumber.

ecologically extinct: Populations are so greatly reduced relative to past levels that the species no longer fulfills its former ecological/functional role

ecosystem functions: Processes performed by ecosystems, including, among other things, primary and secondary production, respiration, nutrient cycling, and decomposition (EPA 2005).

ecosystem services: Benefits that human populations receive from ecosystems.

Environmental Impact Statement (EIS): A document required of federal agencies by the National Environmental Policy Act for major projects or legislative proposals significantly affecting the environment. A tool for decision-making, it describes the positive and negative effects of the undertaking and cites alternative actions (EPA 2010).

Essential Fish Habitat (EFH): Describes all waters and substrate necessary for fish for spawning, breeding, feeding, or growth to maturity.

fore reef zone: The area along the seaward edge of the reef crest that slopes into deeper water on the barrier or fringing reef type (Costa et al. 2013).

functional organization: Trophic interactions such as the relationships between the feeding habits of organisms and/or flow of materials and energy.

global climate change: Refers to a suite of changes in the Earth's climate, including phenomena such as global warming, severe storm frequency and intensity, and glacial melting. Increasingly, scientists believe that global climate change is accelerating due to anthropogenic inputs of CO_2.

gorgonians: Corals having a horny or calcareous branching skeleton (e.g., Sea Fans).

habitat: A place where the physical and biological elements of ecosystems provide a suitable environment including the food, cover, and space resources needed for plant and animal livelihood (Bradley et al. 2010).

Habitat Areas of Particular Concern (HAPC): Discreet subsets of Essential Fish Habitat (EFH) that are rare, particularly susceptible to human-induced degradation, especially ecologically important, or located in an environmentally stressed area.

hardbottom: Shallow and deep-water habitats with solid floor that can provide an attachment surface for sessile organisms such as corals.

herbivore: An animal that feeds on plants (EPA 2010).

historical condition: The ecological condition at some previous point in history. Conditions reflective of the historic time period may no longer exist in actual ecosystems in an area.

human disturbance: Human activity that alters the natural state and can occur at or across many spatial and temporal scales.

hydrology: The scientific study of the movement, distribution, and quality of water on Earth

indicator: A measured characteristic that indicates the condition of a biological, chemical or physical system.

Integrated Taxonomic Information System (ITIS): An American partnership of federal agencies designed to provide consistent and reliable information on the taxonomy of biological species.

integrity: The extent to which all parts or elements of a system (e.g., an aquatic ecosystem) are present and functioning.

intermediate sensitive taxa: Taxa with restricted, geographically isolated distribution patterns (occurring only in a locale as opposed to a region), often due to unique life history requirements. May be long-lived, late maturing, low fecundity, limited mobility, or require mutualist relation with other species. May be listed as threatened, endangered (under federal or local threatened and endangered species laws) or species of special concern. Predictability of occurrence often low, therefore, requires documented observation. Recorded occurrence may be highly dependent on sample methods, site selection and level of effort (EPA 2005).

intermediate tolerance taxa: Taxa that comprise a substantial portion of natural communities, which may increase in number in waters which have moderately increased organic resources and reduced competition, but they are intolerant of excessive pollution loads or habitat alteration. These may be r-strategists (early colonizers with rapid turnover times; boom/bust population characteristics), eurythermal (having a broad thermal tolerance range), or have generalist or facultative feeding strategies enabling them to utilize more diversified food types. They are readily collected with conventional sample methods (EPA 2005).

keystone taxa: A species that has a disproportionately large effect on its environment relative to its abundance (Paine 1995).

least disturbed condition: The best available existing conditions with regard to physical, chemical, and biological characteristics or attributes of a waterbody within a class or region. These waters have the least amount of human disturbance in comparison to others within the waterbody class, region or basin. Least disturbed conditions can be readily found but may depart significantly from natural, undisturbed conditions or minimally disturbed conditions. Least disturbed condition may change significantly over time as human disturbances change (EPA 2005).

levels: In the context of this report, levels are the discrete ratings of biological condition along a stressor-response curve (e.g., BCG Level 1 = excellent condition, BCG Level 6 = completely degraded).

LIDAR (Light Detection and Ranging): A surveying technology that measures distance by illuminating a target with a laser light.

linear reefs: Are linear coral formations that are oriented parallel to shore or the shelf edge. They follow the contours of the shore/shelf edge. This category of reefs may apply to commonly used terms such as fore reef, fringing reef, and shelf edge reef.

live coral cover: A measure of the proportion of reef surface covered by live stony corals.

macroinvertebrates: Animals without backbones of a size large enough to be seen by the unaided eye and which can be retained by a U.S. Standard No. 30 sieve (28 meshes per inch, 0.595 mm openings) (Bradley et al. 2010).

mangroves: Salt-tolerant woody plants that grow in muddy swamps inundated by tides, offshore cays, and along shallow coastlines. Mangrove plants form communities that help stabilize banks and coastlines (Conservation International 2009).

marine protected areas: Any clearly-delineated, managed marine area that contributes to protection of natural resources in some manner (Dudley 2008). Marine reserves are one type of marine protected area where extraction of resources is prohibited (IUCN-WCPA 2008).

megafauna: Animals of large or very large size (e.g., whales, sharks, etc.).

metadata: Structured information that describes, explains, locates, or otherwise makes it easier to retrieve, use, or manage data.

metric: Measurable quantity of an attribute empirically shown to change in value along a gradient of human influence. A dose-response context is documented and confirmed.

minimally disturbed condition: The physical, chemical, and biological conditions of a waterbody with very limited or minimal human disturbance in comparison to others within the waterbody class or region. Minimally disturbed conditions can change over time in response to *natural* processes (EPA 2005).

model: A physical, mathematical, or logical representation of a system of entities, phenomena, or processes; i.e., a simplified abstract view of the complex reality. For example, meteorologists use models to predict the weather.

model calibration: The process of adjustment of the model parameters and forcing within the margins of the uncertainties to obtain a model representation of the assemblage

model validation: The set of processes and activities intended to verify that the model is performing as expected, in line with its design objectives and intended uses.

monitoring: A periodic or continuous measurement of the properties or conditions of something, such as a waterbody.

mollusk: An invertebrate animal with a soft body which typically has a "head" and a "foot" region. Often their bodies are covered by a hard exoskeleton (e.g., clams, scallops, oysters and chitons).

monotonic: A function between ordered sets that preserves or reverses the given order, and must be either entirely non-increasing, or entirely non-decreasing.

multimetric index: An index (expressed as a single numerical value) that integrates several biological metrics to indicate the environmental status of a place.

native species: Species that originated in their location naturally and without the involvement of human activity or intervention.

non-native species: Any species that is not naturally found in that ecosystem. Species introduced or spread from one region to another outside their normal range are non-native or non-indigenous, as are species introduced from other continents (EPA 2005).

nutrients: Chemicals needed by plants and animals for growth (e.g., nitrogen, phosphorus). In water resources, if other physical and chemical conditions are optimal, excessive amounts of nutrients can lead to degradation of water quality by promoting excessive growth, accumulation, and subsequent decay of plants, especially algae. Some nutrients can be toxic to animals at high concentrations.

ocean acidification: The decrease in the pH of the Earth's oceans caused by the uptake of carbon dioxide (CO2) from the atmosphere. When atmospheric carbon dioxide dissolves in seawater produces carbonic acid, which subsequently lowers pH of surrounding seawater, decreases the availability of carbonate (CO2− 3) ions, and lowers the saturation state of the major shell-forming carbonate minerals. Current research indicates the impact of ocean acidification on marine organisms will largely be negative, and the impacts may differ from one life stage to another.

ornamental species: A generic term to describe aquatic animals kept in the aquarium hobby, including fishes, invertebrates such as corals, crustaceans (e.g., crabs, hermit crabs, shrimps), mollusks (e.g., snails, clams, scallops), and also live rock (e.g., rock encrusted with, and containing within its orifices, a wide variety of marine organisms including algae and colorful sessile invertebrates).

pelagic species: Inhabit the water column – being neither close to the bottom nor near the shore – in contrast with reef fish, which are associated with coral reefs. Examples include sharks, barracuda and jacks.

piscivore: A carnivorous animal which eats primarily fish.

pour point: The point on the surface at which water flows out of an area. It is the lowest point along the boundary of a watershed.

Quality Assurance (QA): The process of profiling the data to discover inconsistencies and other anomalies in the data, as well as performing data cleansing activities (e.g. removing outliers, missing data interpolation) to improve the data quality .

reference condition: The condition that approximates natural unimpacted conditions (biological, chemical, physical, etc.) for a waterbody. Reference condition (biological integrity) is best determined by collecting measurements at a number of sites in a similar waterbody class or region under undisturbed or minimally disturbed conditions (by human activity), if they exist. Reference condition is used as a benchmark to determine how much other water bodies depart from this condition due to human disturbance (EPA 2005).

resilience: The ability of an ecosystem to maintain key functions and processes in the face of (human or natural) stresses or pressures, either by resisting or adapting to change (Nyström and Folke 2001; TNC 2009).

rugosity: A measure of small-scale variations or amplitude in the height of a surface. In coral biology, high rugosity is often an indication of the presence of coral, which creates a complex surface as it grows. A rugose sea floor's tendency to generate turbulence is understood to promote the growth of coral and coralline algae by delivering nutrient-rich water after the organisms have depleted the nutrients from the envelope of water immediately surrounding their tissues (Wikipedia 2009).

seagrasses: Flowering plants from one of four plant families (Posidoniaceae, Zosteraceae, Hydrocharitaceae, or Cyomodoceaceae), all in the order Alismatales (in the class of monocotyledons), which grow in marine, fully-saline environments (Wikipedia 2009).

secondary data sources: Data previously collected for a different intended use. Sources include: publicly-available databases; published literature; reports and handbooks generated and submitted by 3rd parties; state and local monitoring programs; unpublished research results; output generated by existing models; previously-performed pilot studies; and photographs.

sediment: Particles and/or clumps of particles of sand, clay, silt, and plant or animal matter that are suspended in, transported by, and eventually deposited by water or air.

highly sensitive taxa: Taxa that naturally occur in low numbers relative to total population density but may make up large relative proportion of richness. May be ubiquitous in occurrence or may be restricted to certain microhabitats, but because of low density, recorded occurrence is dependent on sample effort. Often stenothermic (having a narrow range of thermal tolerance) or cold-water obligates, commonly k-strategists (populations maintained at a fairly constant level, slower development, longer life-span), may have specialized food resource needs or feeding strategies. Generally intolerant to significant alteration of the physical or chemical environment; are often the first taxa observed to be lost from a community (EPA 2005).

sensitive taxa: Taxa that are intolerant to a given anthropogenic stress, often the first species affected by the specific stressor to which they are “sensitive" and the last to recover following restoration (EPA 2005).

sensitive or regionally endemic taxa: Taxa with restricted, geographically isolated distribution patterns (occurring only in a locale as opposed to a region), often due to unique life history requirements. May be long lived, late maturing, low fecundity, limited mobility, or require mutualist relation with other species. May be listed as threatened, endangered or of special concern species. Predictability of occurrence often low, therefore, requires documented observation. Recorded occurrence may be highly dependent on sample methods, site selection and level of effort (EPA 2005).

sessile: Permanently attached or established; not free to move about (e.g., *sessile* sponges and corals)

shifting baseline: A term used to describe the way significant changes to a system are measured against previous baselines, which themselves may represent significant changes from the original state of the system (Wikipedia 2009).

Spawning Aggregation Zone (SPAG): A group of fish gathered for the purpose of reproduction, with individual densities higher than those normally found during non-reproductive periods (Domeier and Colin 1997).

species: A category of taxonomic classification, ranking below a genus or subgenus and consisting of related organisms capable of interbreeding. Also refers to an organism belonging to such a category.

species composition: All of the organisms within a specific ecosystem or area; usually expressed as a percent contribution of individual species or species groups.

species richness: The number of different species represented in an ecological community, landscape or region.

sponge: A multicellular organism that has a body full of pores and channels allowing water to circulate through it; usually occur in sessile colonies.

stock assessments: Provide fisheries managers with information (biological and fisheries data) to regulate a fish stock.

stony corals: A group of coral species known as hard coral that form the hard, calcium carbonate skeleton (e.g., brain corals, fungus or mushroom corals, staghorn, elkhorn, table corals).

stressors: Physical, chemical and biological factors that adversely affect aquatic organisms (Bradley et al. 2010).

taxa: A grouping of organisms given a formal taxonomic name such as species, genus, family, etc. (EPA 2005).

taxa richness: The number of different species represented in an ecological community, landscape or region.

taxa of intermediate tolerance: Taxa that comprise a substantial portion of natural communities, which may increase in number in waters which have moderately increased organic resources and reduced competition, but they are intolerant of excessive pollution loads or habitat alteration. These may be r-strategists (early colonizers with rapid turn-over times; boom/bust population characteristics), eurythermal (having a broad thermal tolerance range), or have generalist or facultative feeding strategies enabling them to utilize more diversified food types. They are readily collected with conventional sample methods (EPA 2005).

taxonomic: Referring to the science of hierarchically classifying animals by categories (phylum (pl. phyla), class, order, family, genus (pl. genera), species and subspecies) that share common features and are thought to have a common evolutionary descent.

tolerant taxa: Taxa that comprise a low proportion of natural communities. Tolerant taxa often are tolerant of a broader range of environmental conditions and are thus resistant to a variety of pollution or habitat-induced stress. They may increase in number (sometimes greatly) in the absence of competition. They are commonly r-strategists (early colonizers with rapid turnover times; boom/bust population characteristics), able to colonize when stress conditions occur. Last survivors (EPA 2005).

topography: The physical features of a surface area including relative elevations and the position of natural and man-made (anthropogenic) features.

total biomass: The mass of living biological organisms in a given area or ecosystem at a given time; either *species biomass*, which is the mass of one or more species, or *community biomass*, which is the mass of all species in the community.

trophic: Describing the relationships between the feeding habits of organisms in a food chain.

turbidity: The amount of solid particles that are suspended in water and that cause light rays shining through the water to scatter. Thus, turbidity makes the water cloudy or even opaque in extreme cases. High levels of turbidity are harmful to aquatic life.

water quality: A term for the combined biological, chemical, and physical characteristics of water with respect to its suitability for a beneficial use.

water quality criteria: Elements of State water quality standards, expressed as constituent concentrations, levels, or narrative statements, representing a quality of water that supports a particular use. When criteria are met, water quality will generally protect the designated use (40 CFR 131).

water quality standards: Provisions of State or Federal law which consist of a designated use or uses for the waters of the United States, water quality criteria for such waters based upon such uses. Water quality standards are to protect public health or welfare, enhance the quality of the water and serve the purposes of the Act (40 CFR 131).

Appendix B – BCG Attributes

Attribute	Description
I. Historically documented, long-lived, or regionally endemic taxa	Taxa known to have been supported according to historical, museum or archeological records, or taxa with restricted distribution (occurring only in a locale as opposed to a region), often due to unique life history requirements. They may be long-lived and late maturing and have low fecundity, limited mobility, multiple habitat requirements as with diadromous species, or require a mutualistic relationship with other species. They may be among listed Endangered or Threatened (E/T) or special concern species. Predictability of occurrence is often low, and therefore requires documented observation. The taxa that are assigned to this category require expert knowledge of life history and regional occurrence of the taxa to appropriately interpret the significance of their presence or absence. Long-lived species are especially important as they provide evidence of multi-annual persistence of habitat condition. Caribbean Coral Reef Fish Examples: *Carcharhinus perezii* (Caribbean Reef Shark), *Mycteroperca bonaci* (Black Grouper), and *Scarus coelestinus* (Midnight Parrotfish)
II. Highly sensitive taxa	Taxa that are highly sensitive to pollution or anthropogenic disturbance. Tend to occur in low numbers relative to total population density, but they might make up a large relative proportion of richness. In high quality sites, they might be ubiquitous in occurrence or might be restricted to certain micro-habitats. They often have slow growth – long-lived (K-strategists) vs. short-lived—fast growth (r-strategists). In coral reef ecosystems, large-bodied, slow-growing, late-maturing fishes (K-strategists) are generally more sensitive to fishing pressure and environmental stress than faster-growing, shorter-lived species (Beverton and Holt 1957; Man et al. 1995; Jennings *et al.* 1998; Coleman et al. 2000; Goodwin *et al.* 2006; Ault et al. 2008). The distinguishing characteristic for this attribute category was found to be sensitivity and not relative rarity, although some of these taxa might be uncommon in the data set (e.g., very small percent of sample occurrence or sample density), therefore, these are the first to disappear with disturbance or pollution. Caribbean Coral Reef Fish Examples: *Aluterus scriptus* (Scrawled Filefish), *Clepticus parrae* (Creole Wrasse) *Haemulon chrysargyreum* (Smallmouth Grunt) and *Pareques acuminatus* (Highhat)

Attribute	Description
III. Intermediate sensitive taxa	Taxa that are abundant in relatively undisturbed conditions but are sensitive to anthropogenic disturbance/pollution. They have a broader range of tolerance than Attribute II taxa and can be found in reduced density and richness in moderately disturbed or polluted stations. These taxa often comprise a substantial portion of natural communities. Caribbean Coral Reef Fish Examples: *Chaetodon capistratus* (Foureye Butterflyfish), *Haemulon flavolineatum* (French Grunt), *Lutjanus mahogoni* (Mahogany Snapper) and *Pomacanthus paru* (French Angelfish)
IV. Intermediate tolerant taxa	Taxa that commonly comprise a substantial portion of the fish assemblage in undisturbed habitats, as well as in moderately disturbed or polluted habitats. They exhibit physiological or life-history characteristics that enable them to thrive under a broad range of thermal, flow, or oxygen conditions. Many have generalist or facultative feeding strategies enabling utilization of diverse food types. These species have little or no detectable response to moderate stress, and they are often equally abundant in both reference and moderately stressed sites. Some intermediate tolerant taxa may show an "intermediate disturbance" response, where densities and frequency of occurrence are relatively high at intermediate levels of stress, but they are intolerant of excessive pollution loads or habitat alteration. Caribbean Coral Reef Fish Examples: *Abudefduf saxatilis* (Sergeant Major), *Carangoides ruber* (Bar Jack), *Ocyurus chrysurus* (Yellowtail Snapper) and *Sparisoma aurofrenatum* (Redband Parrotfish)
V. Tolerant taxa	Tolerant taxa are those that typically comprise a low proportion of natural communities. These taxa are more tolerant of a greater degree of disturbance and stress than other organisms and are, thus, resistant to a variety of pollution or habitat induced stress. They may increase in number (sometimes greatly) under severely altered or stressed conditions. They may possess adaptations in response to organic pollution, hypoxia, or toxic substances. These are the last survivors in severely disturbed systems and can prevail in great numbers due to lack of competition or predation by less tolerant organisms, and they are key community components of level 5 and 6 conditions. Caribbean Coral Reef Fish Examples: *Gerres cinereus* (Yellowfin Mojarra), *Sphoeroides testudineus* (Checkered Puffer) and *Synodus foetens* (Inshore Lizardfish)

Attribute	Description
VI. Non-native or intentionally introduced species	Any species not native to the ecosystem. Species introduced or spread from one region to another outside their normal ranges are non-native, non-indigenous, or alien species. This attribute represents both an effect of human activities and a stressor in the form of biological pollution. The BCG identifies the presence of native taxa expected under undisturbed or minimally disturbed conditions as an essential characteristic of BCG level 1 and 2 conditions. The BCG only allows for the occurrence of non-native taxa in these levels if those taxa do not displace native taxa and do not have a detrimental effect on native structure and function. Condition levels 3 and 4 depict increasing occurrence of non-native taxa. Extensive replacement of native taxa by tolerant or invasive, non-native taxa can occur in levels 5 and 6. Caribbean Coral Reef Fish Examples: *Callogobius clitellus* (Saddled Goby) *and Pterois volitans* (Red Lionfish)
VII. Organism condition	Anomalies of the organisms; indicators of individual health (e.g., deformities, lesions, tumors). Note: This attribute is being applied in the coral reef benthic group as measures of disease, bleaching, and mortality. The fish surveys were not designed to observe such anomalies.
VIII. Ecosystem function	Ecosystem function refers to processes required for the performance of a biological system expected under naturally occurring conditions (e.g., primary and secondary production, respiration, nutrient cycling, and decomposition). Assessing ecosystem function includes consideration of the aggregate performance of dynamic interactions within an ecosystem, such as the interactions among taxa (e.g., food web dynamics) and energy and nutrient processing rates (e.g., energy and nutrient dynamics) (Cairns 1977). Additionally, ecosystem function includes aspects of all levels of biological organization (e.g., individual, population, and community condition). Altered interactions between individual organisms and their abiotic and biotic environments might generate changes in growth rates, reproductive success, movement, or mortality. These altered interactions are ultimately expressed at ecosystem-levels of organization (e.g., shifts from heterotrophy to autotrophy, onset of eutrophic conditions) and as changes in ecosystem process rates (e.g., photosynthesis, respiration, production, decomposition).
IX. Spatial and temporal extent of detrimental effects	The spatial and temporal extent of stressor effects includes the near-field to far-field range of observable effects of the stressors on a water body. Such information can be conveyed by biological assessments provided the spatial density of sampling sites is sufficient to convey changes along a pollution continuum (U.S. EPA 2013). Use of a continuum provides a method for determining the severity (i.e., departure from the desired state) and extent (i.e., distance over which adverse effects are observed) of an impairment from one or more sources.

Attribute	Description
X. Ecosystem connectivity	Access or linkage (in space/time) to materials, locations and conditions required for maintenance of interacting populations of aquatic life. It is the opposite of fragmentation and is necessary for persistence of metapopulations and natural flows of energy and nutrients across ecosystem boundaries. Ecosystem connectivity can be indirectly expressed by certain species that depend on the connectivity, or lack of connectivity, within an aquatic ecosystem to fully complete their life cycles and thus maintain their populations. There are two commonly recognized categories of connectivity based upon the typical life history (i.e., two-phase life cycle) of most reef associated fishes: (1) pre-settlement connectivity through larval dispersal and (2) post-settlement connectivity (Aguilar-Perera 2004). Transport of larval reef fish around Puerto Rico, the United States Virgin Islands, and the uninhabited island of Navassa, which comprise the Caribbean portion of the US-EEZ, is poorly understood, and is not reflected in current fish monitoring programs. Post-settlement connectivity involves 1) juveniles that settle in nursery areas and progressively migrate using intermediate habitats as they grow (e.g., mangroves, lagoons and seagrass beds) until reaching deeper adult habitats; or 2) other kinds of migrations, such as those related with feeding and spawning. The BCG Fish experts recommended additional research to better understand the connectivity between sampling locations and non-coral reef habitats and the necessity of such habitats for each fish species. The knowledge gained from such research would support the future development of useful metrics.

Appendix C – BCG Levels

The six Levels of the BCG are described as follows (modified from EPA 2016).

Level 1, Natural or native condition—Native structural, functional, and taxonomic integrity is preserved; ecosystem function is preserved within the range of natural variability. Level 1 represents biological conditions as they existed (or still exist) in the absence of measurable effects of stressors and provides the basis for comparison to the next five Levels. The Level 1 biological assemblages that occur in a given biogeophysical setting are the result of adaptive evolutionary processes and biogeography. For this reason, the expected Level 1 assemblage of a coral reef from the Caribbean will be very different from that of a coral reef in the Pacific. The maintenance of native species populations and the expected natural diversity of species are essential for Levels 1 and 2. Non-native taxa (Attribute VI) might be present in Level 1 if they cause no displacement of native taxa, although the practical uncertainties of this provision are acknowledged (see section 2.2). Attributes I and II (i.e., historically documented and sensitive taxa) can be used to help assess the status of native taxa when classifying a site or assessing its condition.

Level 2, Minimal changes in structure of the biotic community and minimal changes in ecosystem function—Most native taxa are maintained with some changes in biomass and/or abundance; ecosystem functions are fully maintained within the range of natural variability. Level 2 represents the earliest changes in densities, species composition, and biomass that occur as a result of slight elevation in stressors (e.g., increased temperature regime or nutrient pollution). There might be some reduction of a small fraction of highly sensitive or specialized taxa (Attribute II) or loss of some endemic or rare taxa as a result. The occurrence of non-native taxa should not measurably alter the natural structure and function and should not replace any native taxa. Level 2 can be characterized as the first change in condition from natural, and it is most often manifested in nutrient-polluted waters as slightly increased richness and density of either intermediate sensitive and intermediate tolerant taxa (Attributes III and IV) or both.

Level 3, Evident changes in structure of the biotic community and minimal changes in ecosystem function—Evident changes in structure due to loss of some highly sensitive native taxa; shifts in relative abundance of taxa, but sensitive-ubiquitous taxa are common and relatively abundant; ecosystem functions are fully maintained through redundant Attributes of the system. Level 3 represents readily observable changes that, for example, can occur in response to organic pollution or increased temperature. The "evident" change in structure for Level 3 is interpreted to be perceptible and detectable decreases in highly sensitive taxa (Attribute II) and increases in sensitive-ubiquitous taxa or intermediate organisms (Attributes III and IV).

Level 4, Moderate changes in structure of the biotic community with minimal changes in ecosystem function—Moderate changes in structure due to replacement of some intermediate sensitive taxa by more tolerant taxa, but reproducing populations of some sensitive taxa are maintained; overall balanced distribution of all expected major groups; ecosystem functions largely maintained through redundant traits. Moderate changes of structure occur as stressor effects increase in Level 4. A substantial reduction of the two sensitive Attribute groups

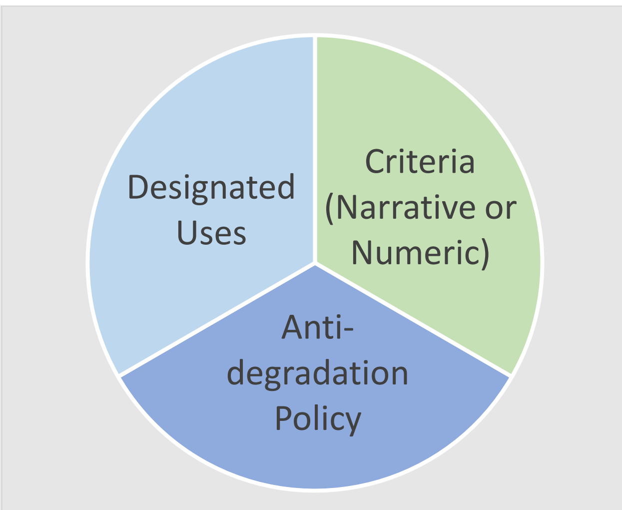
(Attributes II and III) and replacement by more tolerant taxa (Attributes IV and V) might be observed. A key consideration is that some Attribute III sensitive taxa are maintained at a reduced Level, but they are still an important functional part of the system (i.e., function is maintained). While total abundance (density) of organisms might increase, no single taxa or functional group should be overly dominant.

Level 5, Major changes in structure of the biotic community and moderate changes in ecosystem function—Sensitive taxa are markedly diminished or missing; conspicuously unbalanced distribution of major groups from those expected; organism condition shows signs of physiological stress; ecosystem function shows reduced complexity and redundancy; increased build-up or export of unused materials. Changes in ecosystem function (as indicated by marked changes in food-web structure and guilds) are critical in distinguishing between Levels 4 and 5. This could include the loss of functionally important sensitive taxa and keystone taxa (Attribute I, II, and III taxa), such that they are no longer important players in the system, though a few individuals may be present. Keystone taxa control species composition and trophic interactions, and are often, but not always, top predators. As an example, removal of keystone taxa by overfishing has greatly altered the structure and function of many coastal ocean ecosystems (Jackson et al. 2001). Additionally, tolerant non-native taxa (Attribute VI) may dominate some assemblages, and changes in organism condition (Attribute VII) may include significantly increased mortality, depressed fecundity, and/or increased frequency of lesions, tumors, and deformities.

Level 6, Severe changes in structure of the biotic community and major loss of ecosystem function—Extreme changes in structure; wholesale changes in taxonomic composition; extreme alterations from normal densities and distributions; organism condition is often poor; ecosystem functions are severely altered. Level 6 systems are taxonomically depauperate (i.e., low diversity and/or reduced number of organisms) compared to the other Levels. For example, extremely high or low densities of organisms caused by temperature anamolies, overfishing, and/or severe habitat alteration may characterize Level 6 systems. Non-native taxa may predominate.

Appendix D – Clean Water Act (CWA)

The US Clean Water Act (CWA) (33 USC § 1251 et seq. 1972) established a long-term objective to restore and maintain chemical, physical and biological integrity of aquatic resources. The CWA requires states, territories and tribes (herein referred to as "jurisdictions") to adopt water quality standards as provisions of jurisdictional law or regulation. Water quality standards establish the water quality goals for all waters within their jurisdiction, including waters of the territorial seas, and provide a regulatory basis when the water bodies do not meet their designated use(s). Components of Water Quality Standards are shown in **Figure D1**.



Aquatic Life Use (ALU): A designed use in which the water body provides suitable habitat for survival and reproduction of desirable fish, shellfish, and other aquatic organisms (EPA 2009).

Figure D1. Components of Water Quality Standards.

Designated Uses/Aquatic Life Uses. Jurisdictions define the water quality goals of their water bodies by designating the use or uses to be made of each waterbody. Typical designated uses include aquatic life use; recreation; fishing; public drinking water supply; and agricultural, industrial, navigational and other purposes. Aquatic life use (ALU) classes describe the expected biological condition of a jurisdiction's waters. ALUs can cover a continuum of biological conditions, with some waters being closer to an ideal of natural, undisturbed (biological integrity) condition (EPA 2002).

Antidegradation Policy. Each jurisdiction must have an antidegradation policy and a plan to implement that policy. The antidegradation policy is particularly important for outstanding national resource waters (ONRW).

Criteria. Jurisdictions must also set criteria necessary to protect the uses and protect water quality through antidegradation provisions. Water quality criteria are expressed as constituent concentrations, levels or narrative statements, representing a level of water quality that supports a particular use. Jurisdictions now routinely use biological information to directly assess the biological condition of their aquatic resources, track changes in the condition, and develop biological criteria (EPA 2002).

Biological criteria (biocriteria) are benchmark, guideline or threshold values that describe the expected (or desired) condition for aquatic life in waters with a designated aquatic life use.

Narrative biocriteria are statements that describe a desirable biological condition, such as "a balanced, healthy population of native aquatic life." Jurisdictions can define narrative biological criteria early in program development.

To support the narrative criteria, a jurisdiction needs standardized protocols for data collection, analysis and interpretation, that have been vetted through a rigorous scientific process. These protocols provide the legal and programmatic basis for numeric criteria (EPA 1990; Karr 1991).

Numeric biocriteria identify specific thresholds expected to support a designated aquatic life use. For example, assuming protection of coral reef ecosystem "as naturally occurs" is a designated use, numeric biocriteria might include a minimum percentage of coral cover, a minimum number of coral species in a defined region, or a maximum number of nonindigenous fish—at whatever levels are deemed necessary to support the designated use (EPA 2002). When biological condition does not meet a biological criteria that has been formally adopted into a state's or territory's WQS through a formal rulemaking process and approved by USEPA, the waterbody is considered impaired and automatically triggers a regulatory decision.

The Biological Condition Gradient (BCG). Beginning in the late 1990s, EPA collaborated with freshwater biologists and managers from across the United States to develop and implement the Biological Condition Gradient (BCG) (Davies and Jackson 2006; EPA 2016). The BCG is a conceptual framework (**Fig. D2**) that describes how biological attributes of aquatic ecosystems (i.e., biological condition) is expected to change along a gradient of increasing anthropogenic stress (e.g., physical, chemical and biological impacts). The BCG is now a recognized tool in the water quality management toolbox.

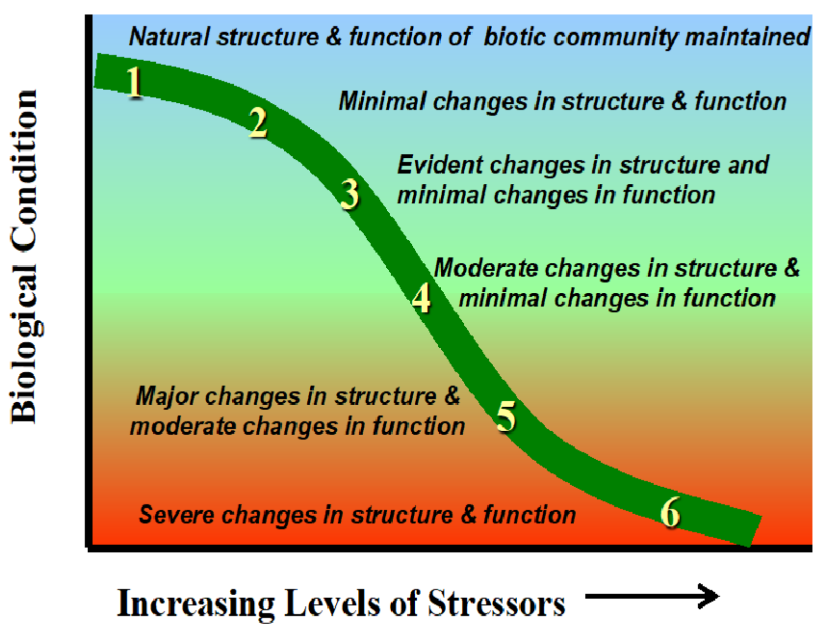


Figure D2. The Biological Condition Gradient (BCG).

Appendix E – BCG Workshops and Webinars

First Workshop (2012) – Proof of Concept. The workshop was held at the Caribbean Coral Reef Institute in La Parguera, Puerto Rico, on August 21-22, 2012.

The experts evaluated photos and videos for 12 stations collected during EPA coral reef surveys (2010 and 2011) from Puerto Rico coral reefs exhibiting a wide range of conditions. The experts individually rated each station as to observed condition (good, fair or poor) and documented their rationale for the assignment. The group discussed the reef attributes that characterize biological integrity (or the natural condition) for Puerto Rico's coral reefs, which will serve as the baseline condition, since the CWA is grounded in the concept of natural, undisturbed conditions. The experts developed a conceptual Coral Reef BCG with four Levels of Condition.

Webinars following the first workshop.

2012 Workshop Summary and Overview. Since some experts could not attend the first workshop, we provided a PowerPoint presentation of the workshop process, including 3 videos representing best, fair and worst stations embedded into the presentation. Showed them the completed conceptual model.

Generalized Stressor Gradient (23 Jan 2014). EPA and the expert panel discussed the concept of a generalized stressor axis (GSA) and focused on three stressors that should be considered for coral reefs: (1) land-based sources of pollution, (2) fishing pressure, and (3) global climate change-associated thermal anomalies.

Updates, Data, Species Sensitivity (20 Feb 2014). Presented a review of EPA and NOAA survey methods, discussion of differences and possible biases associated with each.

Shared the EPA efforts to capture a wide range of species-specific data and reference citations into a single spreadsheet.

Workshop 2 (2014). The 2nd BCG workshop was held at El Yunque National Forest Headquarters, Puerto Rico, on April 8-10, 2014. Broke into two groups: benthic organisms and fish.

Fish. The fish breakout group assigned 128 species (fish observed during EPA's 2010 and 2011 surveys in Puerto Rico) to BCG attributes. The stressor categories that the experts considered most relevant to fish were land-based sedimentation and fishing pressure. For fishing pressure, the experts considered whether the species was subject to fishing pressure, the category of fishing (recreational, aquarium or commercial) and whether the species was regulated.

The fish experts assigned 38 samples (EPA 2010 and 2011 data) to BCG levels. Panel members identified several indicators and metrics that they used to distinguish BCG levels, including taxa richness; total biomass; sensitive taxa; density of damselfish, piscivores, and other fishes.

Benthic Organisms. The benthic experts assigned 46 scleractinian and hydrozoan hard coral species found in the Western Atlantic to attributes I–V that defined different levels of sensitivity and tolerance to specific human-induced stressors. The experts agreed that thermal anomalies and land-based stressors were the most critical threats to corals, and all agreed that the stressors must be independently evaluated, because there is no evidence to suggest the same species would have the same sensitivity to multiple stressors.

EPA Effort following the 2nd Workshop. Following the 2nd workshop, EPA and Tetra Tech developed quantitative rules for the fish model using the experts' narrative statements and the box plots to assign numbers to the narrative rules. Some rules suggested by the panel (e.g., species per family in Levels 3 and 4; damselfish and wrasses in Level 4, and piscivores in level 4) were either ineffective or redundant and were not used. Rules are expressed as inequalities (e.g., Level 3 sites have more than 14 species and less than 25% damselfish density), and in this formulation the rules must be "true" for a site to retain membership in the given level. For example, observations that there are fewer species and more damselfish in Level 4 sites than in Level 3, contributes to the rules for Level 3, but not to Level 4 rules.

Webinars following second workshop:

Reef classification (Benthic Group) (26 Feb 2015). Presentation on reef habitat classification derived from the NOAA Biogeography Caribbean classification scheme. Evaluated 4 samples and discussed how these related to the habitat classification.

Assigned sites to BCG Levels (Benthic Group) (29 April 2015). Evaluated four samples and assigned BCG levels. Discussed how these samples related to the fore reef zone agreed upon for reef classification.

Reviewed quantitative rules (Fish Group) (7 May 2015). Presentation on fish experts' progress. Reviewed draft quantitative rules. Looked at 4 NOAA stations chosen to be comparable to the EPA sites – decided the surveys were not comparable.

Assigned sites to BCG Levels (Fish Group) (May 25, 2015).

Assigned sites to BCG Levels (Benthic Group) (26 June 2015). Presentation on progress of fish group and preliminary fish rules. Evaluated more stations. 4 metrics provided for each species observed at the station: density (m^2), 3D colony surface area (cm^2/m^2), 2D colony surface area (cm^2/m^2), % mortality

Assigned sites to BCG Levels (Benthic Group) (16 July 2015).

Workshop 3 (2015) third workshop held at the International Institute of Tropical Forestry (IITF), in San Juan, Puerto Rico, on October 13 – 15, 2015.

Fish. The objective for the fish group was to improve the agreement between the expert ratings and the scores predicted by the preliminary quantitative fish model. The group reviewed 11 confirmation sites and applied the fish rules that had been established in Workshop 2 to assign a BCG level to each site. The experts requested, and EPA provided, the size structure distributions for all stations and for each species. Using the confirmation sites the model correctly predicted 9 (82% correct).

There was also a presentation about BCG Attribute X – Connectivity, followed by a facilitated discussion. The presentation covered basic landscape ecology concepts including structure, function and landscape metrics. The experts felt that high-resolution reef bottom topography (LIDAR or other) was critically needed to so that features related to connectivity would be recognizable and quantifiable. High-resolution topography would also indicate elements of rugosity as well as connectivity, allowing characterization of broad-scale relief and a possible basis for classification of reefs. This project would require coordination among multiple agencies.

Webinars following the 3rd Workshop.

Fish species assignment to BCG attributes (Fish Group only). The experts assigned the remaining 229 species to BCG Attributes I-VI based upon sensitivity to anthropogenic stress, historic species importance in the Caribbean, and whether native or exotic. The information was captured in a spreadsheet, including the assigned attribute, the species name, common name (English), guild, # observed during EPA and NOAA PR surveys, rationale for attribute assignment, and unresolved comments.

Update on Fish break-out group (all experts). Updated and presented all boxplots and histograms to include verification samples. Identified remaining issues, such as habitat effects and possible classification issues, effects of distance from shore and connectivity, effects of fishing pressure, interpreting fish size structure is important, biomass could be expressed differently, and water quality information would help.

Update on Benthic break-out group (all experts). The experts expressed that there was a lack of metrics like 2D % coral cover, health condition metrics of corals/octocorals, a need for metrics on benthic community cover addressing algae, octocorals, zoanthids, sponges subgroups, sediment/substrate and "standing dead" coral. There was also a need for recruitment measures and water quality (clarity, temperature, DO). The rugosity measurement needed refinement to determine what used to be there, what could live there, what is the apparent bioerosion rate. Rugosity could indicate what kind of reef it was, rather than how degraded it is (geological history). The experts were dependent on videos but recognized that poor quality videos might affect ratings.

Update on Coral Reef Biocriteria in USVI and Puerto Rico (all experts) (April 2017). Discussed site selection criteria, e.g., don't sample and compare different habitat types. Define sampling to focus on the fore-reef, shallow and deep, as the best reef class for consistent assessment. Also considered how to evaluate organism condition and disease. Decided that additional data needed included % 2D coral cover (more intuitive than 3D cm2 surface area), health of colonies, and algal coverage (CCA, fleshy, turf, filamentous, cyanobacteria). It was suggested to use NOAA NCRMP data. Examples were presented on LPI and DEMO data from NCRMP. Again, there was an emphasis on sampling protocols and increased replication of shorter transects (10m).

Reef Benthic BCG: Rule Development (Sept 29, 2017). Results from sample ratings of 39 NCRMP samples rated in 2017. Box plots by assigned BCG Level were presented as a step in establishing numeric rules. Rules were drafted and presented for expert discussion.

Benthic and fish updates (April, 2018) Agenda items included: Welcome and webinar purpose, BCG Concepts (very brief review), Level definitions, , Level narrative rules, Level quantitative rules, Project progress report, Metric patterns with BCG levels, Draft BCG models, New sample ratings and homework.

Expert ratings of benthic stations (Benthic Group) (18 June 2018). Agenda items included: Welcome and webinar purpose, Review samples with consistent or variable ratings, Level descriptions (Definition, Narrative, Semi-quantitative rules, Model rules), and St Croix homework assignment. Reviewed 3 stations rated by experts as homework. Discussion of rules that could be tested with box plots.

Workshop 4 (2019) fourth and final workshop held at the Caribbean Coral Reef Institute in La Parguera, Puerto Rico, on March 12 – 14, 2019, preceded by a Fish Expert Meeting on March 11th.

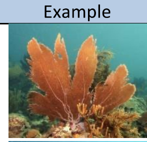
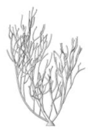
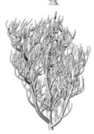
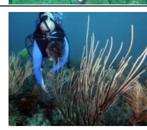
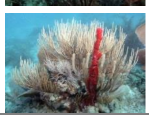
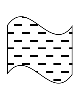
Webinars following the 4th Workshop.

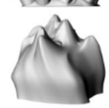
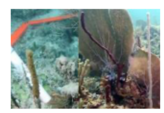
Benthic model update and review of samples (February 2019). Agenda items included: Sampling Methods Review (LPI and DEMO), Sample Review for Re-calibration (Samples rated by the experts at each end of the BC Gradient, Samples with expert agreement and with high variability), Model Description, Model Mismatches.

Benthic model validation results (July 2020). Agenda items included: Validation Summary Table (Very Good Agreement!), Reminder slides (Model rules, Levels and Attributes commonality, Level qualifiers), Model Issues, Sample review slides, and Screening Model.

Appendix F – Gorgonian and Sponge Morphological Shapes

With simulated models and *in situ* examples (Santavy et al. 2012). The gorgonian morphologies are shown in the left table and the sponges in the right.

Gorgonian Morphology		Simulated Model	*in situ* Example
Sea Fans *(Gorgonia ventalina, Leptogorgia)*	Planar		
(Gorgonia flabellum)	Three-dimensional		
Sea Rods branch and branchlet diameter ≥ 15 - ≤30mm	Unbranched (digitate form, *Briareum*)		
	Branched *(Plexaura)*		
	Bushy *(Eunicea fusca)*		
	Planar *(Eunicea tourneforti)*		
Sea Whips branch & branchlet diameter ≥5 - ≤15mm	Branched *(Pterogorgia)*		
	Bushy *(Pterogorgia guadalupensi)*		
Sea Plumes smallest branch & branchlet diameter usually ≤5mm *(Muriceopsis flavida, Pseudopterogorgia)*			
Encrusting Gorgonians *(Briareum, Erythopodium)*			

Sponge Morphology (spp. example)	Simulated Model	*in situ* Example
Barrel ***(Xestospongia muta, Verongula reiswigi)***		
Vase ***(Callyspongia plicifera, Callyspongia vaginalis)***		
Globe ***(Iricinia strobilina, Spheciospongia vesparium)***		
Tube ***(Aplysina archeri, Aplysina fistularis)***		
Mound ***(Oligoceras hemorrhages, Iricinia felix)***		
Rod ***(Aplysina cauliformis, Niphates erecta)***		
Bushy ***(Aplysina fulva)***		
Branched Ropey ***(Iotrochota birotulata)***		
Encrusting ***(Amphimedon compressa, Chrondrilla caribensis)***		
Boring ***(all Clionids)***		

Appendix G – Coral Metric Calculations

Metrics were calculated to represent taxa richness, relative richness, taxa density, and percent cover of coral and other benthic organisms observed within the sampled transects. Metrics were also calculated with limitations by taxonomy or taxa traits, e.g. the BCG attributes, fish trophic group, or coral mortality. For the LPI data, each point was 1% of coverage. Taxa richness and percent coverage was calculated by summation of the point data for the whole transect.

The coral demographic metrics (adapted from Santavy et al. 2012; Bradley et al. 2014b) were Colony Surface Area (CSA), Live tissue area on Colony Surface Area (LCSA), based on both 2-dimensional and 3-dimensional calculations. The CSA_3D was the total surface area (cm2) of a single colony, which includes both living tissue covering the skeleton and dead portions on the three-dimensional skeletal surface, such that:

$$CSA = \pi r^2 M \tag{1}$$

$$\text{where, } r = [h\_cm + (d\_cm/2)] / 2 \tag{2}$$

The variables used to calculate r were: h_cm=maximum colony height (cm), d_cm=maximum colony diameter (cm), and M = morphological conversion factor. In general, morphological types and relative values included flat (M=1), hemisphere (M=2), overlapping plates and lobes (M=3), and branched (M=4) colonies. The LCSA_3D was the total surface area (cm2) of a single colony including only the living tissue that covered the skeletal surface and was calculated as:

$$LCSA = CSA\ (\%LT/100) \tag{3}$$

Where %LT was the estimated percent of colony surface area that contained live tissue. In 2 dimensions, surface area was an estimated value of the total planar colony surface area (cm2) as though it were viewed only from directly above the colony. The total colony area (CSA_2D) and the area of living tissue (LCSA_2D) were estimated as:

$$CSA\_2D = \pi\ [2r\ (cm)/2]^2 \tag{4}$$

$$LCSA\_2D = \pi\ [2r\ (cm)/2]^2 * (\%LT/100) \tag{5}$$

Metrics were calculated based on surface area and prevalence of colonies based on species BCG attributes and ecological traits. Metrics were formulated to replicate the narrative rules expressed by the expert panel. For a metric example, LCSA_2D of large, reef building coral was calculated by limiting the surface area calculations to those species that are typically massive enough to add structure to the reef. In this example, the large reef building coral include *Acropora cervicornis, Acropora palmata, Acropora prolifera, Colpophyllia natans, Diploria labyrinthiformis, Dendrogyra cylindrus, Montastraea cavernosa, Orbicella annularis, Orbicella faveolata, Orbicella franksi, Pseudodiploria clivosa, Pseudodiploria strigosa* and *Siderastrea siderea*.

Appendix H – BCG Coral Reef Experts

Richard Appeldoorn
University of Puerto Rico
Department of Marine Sciences
Mayaguez, PR, 00681 9013
787-899-2048 x 251
Richard.appeldoorn@upr.edu

Jerry Ault
University of Miami (RSMAS/MBF)
4600 Rickenbacker Causeway
Miami, FL 33149
305-421-4884
jault@rsmas.miami.edu

David Ballantine
Department of Botany, NMNH
Smithsonian Institution
10th St. & Constitution Ave. NW
Washington, DC, 20560
ballantined@si.edu

Jorge Bauzá
San Juan Bay Estuary Program
32 Cascada, Muñoz Rivera
Guaynabo, PR, 00969
787-638-9979
jbauza@estuario.org

Miguel Canals (Menqui)
Puerto Rico DNER, retired
787-821-5706
menqui@hotmail.com

Lisamarie Carrubba
NOAA Fisheries, Office of Protected Resources
1315 East-West Highway
Silver Spring, MD 20910
301-427-8493
Lisamarie.carrubba@noaa.gov

Randy Clark
NOAA NCOS, Marine Spatial Ecology Div.
1021 Balch Blvd, Suite 1003
Stennis Space Center, MS 39529
228-688-3732
Randy.clark@noaa.gov

David Cuevas
US EPA, Region 2
Caribbean Environmental Protection Div.
48 CARR 165km 1.2
City View Plaza II, Suite 7000
Guaynabo, PR, 00968-8073
787-977-5856
Cuevas.david@epa.gov

Ernesto Diaz
Puerto Rico DNER, CZMP
PO Box 366147
San Juan, PR 00936
787-999-2200 x2729
ediaz@drna.pr.gov

William Fisher
US EPA, ORD, GED
1 Sabine Island Dr.
Gulf Breeze, FL 32563
850-934-9394
Fisher.william@epa.gov

Edwin A. Hernández-Delgado
University of Puerto Rico
Center Applied Tropical Ecology and
Conservation
PO Box 23360
San Juan, PR 00931-3360
787-764-0000 x2009
Coral_giac@yahoo.com
edwin.hernandez13@upr.edu

Evelyn Huertas
US EPA, Region 2
Caribbean Environmental Protection Div.
City View Plaza II - Suite 7000
Guaynabo, PR, 00968-8069
787-977-5852
Huertas.evelyn@epa.gov

Aaron Hutchins
Island Life Adventures
William Roebuck Industrial Park,
Frederiksted 00850
St. Croix, USVI
aaronhutchins@yahoo.com

Chris Jeffrey
CSS-Dynamac, NOAA
10301 Democracy Lane, Suite 300
Fairfax, Virginia 22030
703-691-4612
Chris.Jeffrey@noaa.gov

Craig Lilyestrom
Retired, formerly PR DNER
161 Cesar Gonzalez St. Box 69
San Juan, PR 00918
Craig_02@icloud.com

Melanie McField
Smithsonian Trust
Healthy Reefs for Healthy People Initiative
1648 NE 47th St
Ft Lauderdale FL 33334
954-990-8842
mcfield@healthyreefs.org

Graciela Garcia Moliner
Caribbean Fishery Management Council
270 Muñoz Rivera Ave. Suite 401
San Juan, PR, 00918-1913
787-766-5926
Graciela.garcia-moliner@noaa.gov

Jeff Miller
Virgin Islands National Park
1300 Cruz Bay Creek,
St. John, VI, 00830
340-693-8950 x227
William_J_Miller@nps.gov

Simon Pittman
Seascape Analytics LTD.
13 Haddington Road
Plymouth
PL2 1RP
United Kingdom
sjpittman@gmail.com

Antares Ramos Alvarez
Integro Foundation
El Caribe 53 Calle Palmeras
San Juan PR 00901-0000
antares.ramos.alvarez@gmail.com

Loretta Roberson
Associate Scientist, The Bell Center
Marine Biological Laboratory
7 MBL Street
Woods Hole, MA 02543 USA
508-289-7097
lroberson@mbl.edu

Caroline S Rogers
USGS Wetland & Aquatic Research Center
Caribbean Field Station
1300 Cruz Bay Creek
St. John, USVI 00830
340 693 8950 x 221
caroline_rogers@usgs.gov

Héctor Ruiz
HJR Reefscaping
P.O. Box 1126
Hormigueros, P.R. 00660
787-691-7410
hectorruizt@me.com

Alberto Sabat
University of Puerto Rico
Department of Biology
PO Box 23360
Rio Piedras, PR 00931-3360
787-764-0000 x2113
amsabat@gmail.com

Michelle Scharer
Caribbean Fishery Management Council
SW Region/HJR Reefscaping
P.O. Box 1442
Boquerón, PR 00622
Michelle.Scharer@upr.edu

Steve Smith
University of Miami, RSMAS (CIMAS)
4600 Rickenbacker Causeway
Miami, FL 33149
305-421-4783
steve.smith@rsmas.miami.edu

Tyler Smith
University of the Virgin Islands
#2 John Brewer's Bay
St. Thomas, VI, 00802-9990
340-693-1394
tsmith@uvi.edu

Alina Szmant
Adjunct Professor, Center for Marine Science
University of North Carolina, Wilmington
5600 Marvin K. Moss Ln
Wilmington NC 28409 USA
910-962-2362
szmanta@uncw.edu

Brandi Todd
Scientific Support Coordinator, NOAA
500 Poydras, Suite 1213
New Orleans, LA 70130
(504) 589-4416
brandi.todd@noaa.gov

Vance Vicente
Vicente & Associates Inc.
Garden Hills Pz 1353 19
Guaynabo, PR, 00966
787-781-6503
vance@prtc.net

Brian K. Walker
National Coral Reef Institute
Nova Southeastern University
8000 N. Ocean Drive
Dania Beach, FL 33004
954-262-3675
walkerb@nova.edu

Ernesto Weil
Department of Marine Sciences
University of Puerto Rico, Mayagüez
PO Box 9000
Mayagüez, Puerto Rico 00681
787-899-2048 x241/272
ernesto.weil@upr.edu; reefpal@gmail.com

Paul Yoshioka
613 NE Emerson St
Port St. Lucie, FL 34983
772-777 2834
paul.yoshioka@upr.edu

Appendix I – Management Observers at Coral Reef BCG Workshops

Juan J. Cruz Motta
Director of the Caribbean Coral Reef Institute
Department of Marine Sciences
University of Puerto Rico, Mayagüez
PO Box 9000
Mayagüez, Puerto Rico 00681
Tel. (787) 899-2048 ext. 228;
juan.cruz13@upr.edu

Damaris Delgado
Puerto Rico DNER
Urb. El Cerezal 1642 Calle Nieper
San Juan PR 00926
787-999-2200 x 2615
ddelgado@drna.gobierno.pr

Annette Feliberty Ruiz
EQB, Point Source Permits Div., WQ
Puerto Rico Environmental Quality Board
P.O. Box 11488
San Juan, PR 00910
787-767-8181
annettefeliberty@jca.pr.gov

Miguel Figuerola
PhD Student of Ernesto Weil, Quant Ecology
Contractor PR DRNA WQ
Department of Marine Sciences
University of Puerto Rico, Mayagüez
PO Box 9000
Mayagüez, Puerto Rico 00681
mgfiguerola@drna.pr.org

Leslie Henderson
VI Depart. Planning and Natural Resources
8100 Lindberg Bay, Suite 61
St. Thomas, USVI 00802
340-626-0402
leslie.henderson@dpnr.vi.gov

Kasey Jacobs
Caribbean Landscape Conservation Coop.
Jardin IITF, Botánico Sur
1201 Calle Ceiba, Río Piedras, PR 00926
787-764-7137
kaseyrjacobs@caribbeanlcc.org

Benjamin Keularts
Environmental Program Manager, WPC/WQM
Division of Environmental Protection, USVI
45 Mars Hill, Frederiksted, VI 00840
340-773-1082 x 2274
benjamin.keularts@dpnr.vi.gov

Jeiger Medina Muñiz
Protectores de Cuencas
Paisage de Escorial
80 Blvd Media Luna 105
Carolina, PR 00987
787-506-5197
jeiger.medina@gmail.com

Ángel R Meléndez-Aguilar
Manager- Water Quality Area
Puerto Rico Environmental Quality Board
P.O. Box 11488
San Juan, PR 00910
787-767-8181 x. 3000, 3001
angelmelendez@jca.pr.gov

Tania M. Metz
Puerto Rico Coral Reef Program Coordinator
Calle Sagrado Corazón 467
Cond. Imperial Suites 401C
San Juan, PR 00915
787-999-2200 x 2406
tmetz@drna.pr.gov

Brent A. Murray
Caribbean Landscape Conservation Coop
Jardín Botánico Sur, USFWS
1201 Calle Ceiba
Río Piedras, PR 00926
787-764-7738
brent_murray@fws.gov

Vanessa Rogers
Environmental Specialist III
Division of Environmental Protection, USVI
340-774-3320 x 5190
vanessa.rogers@dpnr.vi.gov

Lisbeth San Miguel
Puerto Rico Environmental Quality Board
PO Box 11488
San Juan, PR 00918
787-392-2484
lisbethsanmiguel@jca.gobierno.pr

Roberto Viquiera
Protectores de Cuencas,
Guánica Coordinator
Box 673
Yauco, Puerto Rico 00698
787-457-8803
rviqueira@hotmail.com

Stacy Williams
Institute Socio-Ecological Research, Inc (ISER)
P.O. Box 3151, Lajas, PR 00667-3151
stcmwilliams@gmail.com; iser@isercaribe.org

Izabela Wojtenko
EPA Region 2 Clean Water Division
290 Broadway New York,
NY 10007-1866
212-637-3814
Wojtenko.Izabela@epa.gov

Appendix J – BCG Team

Pat Bradley
Tetra Tech
1810 Harris Ave.
Key West, FL 33040
443-326-4884
Patbradley@comcast.net

Alexandra Gallindo
US Fish and Wildlife Service
Caribbean Ecological Services Field Office
P.O. Box 491
Boquerón, PR 00622
787/851 7297
alexandra_galindo@fws.gov

Jeroen Gerritsen
Retired, formerly Tetra Tech
200 Summit blvd
Springfield, OR 97477
410 303-1547
jingyee.jeroen@gmail.com

Christina Horstmann
ORISE Participant, EPA, ORD, GED
1 Sabine Island Dr.
Gulf Breeze, FL 32563
850-934-9247
Horstmann.christina@epa.gov

Susan K. Jackson
Ariel Rios Building; Mail Code: 4304T
1200 Pennsylvania Avenue, N.W.
Washington, DC 20460
202-566-1112
jackson.susank@epa.gov

Ben Jessup
Tetra Tech
73 Main Street #38
Montpelier, VT 05602
802-229-1059
benjamin.jessup@tetratech.com

Leah Oliver
US EPA, ORD, Gulf Ecol. Div.
1 Sabine Island Dr.
Gulf Breeze, FL 32561
850-934-2470
Oliver.leah@epa.gov

Deborah Santavy
US EPA, ORD, Gulf Ecol. Div.
1 Sabine Island Dr.
Gulf Breeze, FL 32561
850-934-9358
santavy.debbie@epa.gov

Appendix K – Development of the Predictive BCG Decision Model

Rule thresholds

The statistical distribution of the metric values in sites assessed by the panel, including modes and quantiles, were used to establish decision thresholds for assigning sites to each BCG level. Mathematical fuzzy logic that mimicked human reasoning was used to develop an inference model to replicate the fish experts' decision process (EPA 2016). Fuzzy logic is "a precise logic of imprecision and approximate reasoning" (Zadeh 2008) that has been directly applied worldwide in environmental assessments where imprecise and incomplete information is used to make decisions on the quality and sustainability of systems (Castella and Speight 1996; Ibelings et al. 2003; Ionnidou et al. 2003; EPA 2016; Gerritsen et al. 2017). The development of BCG inference models is explained specifically in Gerritsen et al. (2017), and a general tutorial on fuzzy logic can be found in Klir (2004).

Model rules were expressed as: *metric* $\geq x$ $(a - b)$, where the metric must be at least the rule threshold (x) and is given partial membership within the range of the minimum rule threshold (a) and the maximum rule threshold (b). Membership in the given level for each rule was interpolated between a (0, not a member) and b (1, certainly a member). This fuzzy range around the threshold accounts for the intrinsic uncertainty about exact quantitative cutoffs. With this rule construction, the quantitative decision model yielded numeric memberships between 0 and 1 for each BCG level for each rule. For the BCG Level 3 fish *total taxa* rule (**Figure 1**), at the midpoint of the range (15), the membership factor is 0.5. The *total taxa* should be a minimum of 10 to indicate any characteristics of Level 3, and full membership is recognized at values above 20. Hence, membership of the site in BCG Level 3 was 0 (zero) when the metric *total tax*a was less than or equal to 10, 50% when there were exactly 15 taxa, and 1 (100%) when the value equaled or exceeded 20.

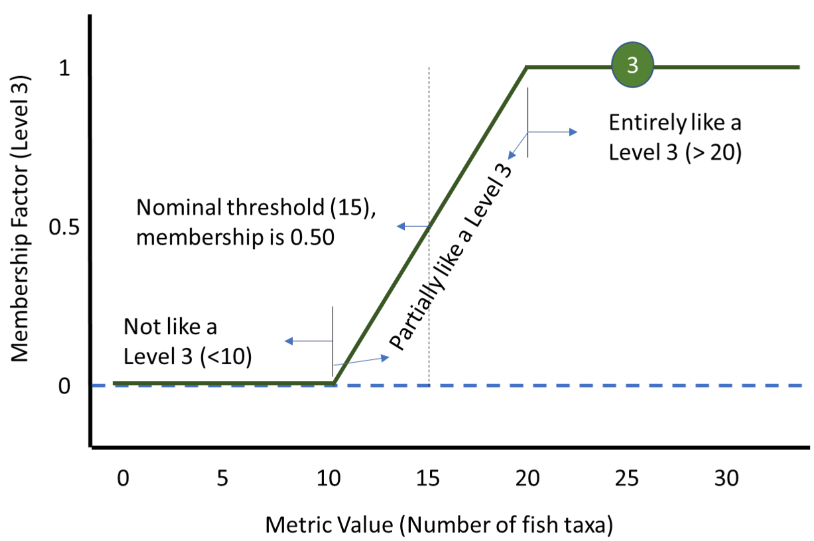


Figure K30. Rule diagram illustrating membership in Level 3 based on the rule: Fish taxa >15 (10 – 20).

When combining multiple rules for any level, the combination strategy used logical operators to describe whether all rules must be met (using the "and" function) or whether only one of a set of rules must be met (using the "or" function). For example, if 4 rules are all required to be met to designate a sample at a level, the combination strategy would be "rule 1 and rule 2 and rule 3 and rule 4". The resulting membership for the BCG level would be the minimum membership of all 4 rules. If combined with the "or" function (rule 1 or rule 2 or rule 3 or rule 4), membership for the level would be the maximum membership of the 4 rules.

Because each rule is interpolated between the minimum and maximum of the threshold range, it is possible to have partial membership for a sample at a level after combining rules. When applying rules in combination and in a cascade from Level 2 through Level 6, partial membership at one level implies that the remainder of the membership is at the next level. This allows for ties between levels, as well as dominant membership in a single level and smaller memberships in an adjacent level. A 0.30 membership factor indicates partial membership in the level being scrutinized and 0.70 membership in the next worst level.

How the model rules are applied

In applying the model rules, the rules for BCG Level 2 (or Level 1 if rules exist) are tested first. If the rules are met, then the model indicates that the sample should be assigned to that Level. If the model indicates non-membership or partial membership, then rules for the next Level are tested. This cascade of rule application continues until membership is decided. Partial membership at any Level implies that the sample has characteristics of that Level and the next in sequence. If no rules are met at Level 5, then the sample is assigned to Level 6 without application of any more rules.

FigureK31. The BCG Rule Application. BCG rules are applied like a cascade. This example is from the Benthic Rules.

Model Perforamce

Performance of the BCG model was described in terms of agreement between model results and the median of expert ratings per site. We assessed the number of sites where the model prediction exactly matched the experts' median opinion ("exact match") and the number of sites where the model predicted a BCG Level that differed from the median expert opinion ("mismatch" sites). For the mismatched sites, differences between the expert ratings and the model predictions were examined to determine whether there was a bias to model predictions or whether the magnitude of the difference was meaningful.

Appendix L – Characterization of BCG Condition Level 1 for coral reefs in Puerto Rico and the US Virgin Islands

Ernesto Weil
Deptartment of Marine Sciences
University of Puerto Rico

Technical Report completed under USEPA Contract 68HERC20D0019

Introduction

Detecting major changes in natural ecosystems requires well-designed and statistically robust monitoring programs to determine biological composition and structure over short- and long-terms to detect trends. Studies that are well-designed, have consistent and standard methods (quality control). Long-term monitoring programs using permanent transects/quadrats are scarce and/or incomplete (few localities or short-term) in the Caribbean. Surveys assessing the same areas using permanent transects over time are the only way to discriminate temporal changes (variability) in community structure and other population descriptors. The spatial variability generated by random/haphazardly placement of transects every time the surveys are done in the same locality are too great to detect these temporal and spatial trends (Miller and Rogers 2016).

Humans are altering coral communities in ways that are unprecedented from the historical record (Pandolfi and Jackson 2006; van Woesik et al. 2012), as historically dominant coral species decline, and weedy, opportunistic and more resistant species increase in abundance and cover over time (Knowlton 2001; McClanahan et al. 2007; Green et al. 2008; Alvarez-Filip et al. 2011; García-Sais et al. 2017). Climate change, overexploitation of resources, pollution, and disease have resulted in global declines of live coral cover, diversity and structural complexity of coral reefs that has been regarded as the world's most complex and biodiverse marine ecosystem (Gardner et al. 2003; Pandolfi et al. 2003; Alvarez-Filip et al. 2009).

However, community shifts in coral species can often be overlooked as they may be subtle because coral species identification is challenging, and substantial community changes may occur on decadal, centennial, or millennial timescales (Pandolfi and Jackson 2006; van Woesik et al. 2012). Changes may be undetectable as the baseline for what is considered a 'normal' community composition today is often unknown and may be different from what was considered 'normal' five, 20 or 100 years ago. Shifts in species composition and changes in live coral cover can occur at different rates depending on the intensity and duration of disturbances, original composition and structure of the coral community, and its location. The widespread mortality of massive reef-building coral species in the US Virgin Islands (USVI) and Puerto Rico (PR) during 2005-2007 did not occur in many other Caribbean localities. The increased thermal anomaly that caused coral bleaching was confined to those regions (Wilkinson and Souter 2008). Five years later, a similar event occurred in the southern Caribbean off the coast of Venezuela, with no massive coral mortalities reported elsewhere in the Caribbean (Jackson et al. 2014). Coral community shifts can be rapid, occurring over a single year or several years, as changes observed in the mid 1980's after mass mortalities of the acroporids (an important foundational species at that time) and the keystone species of sea urchin, *Diadema antillarum* (Gladfelter 1982; Lessios et al. 1984; Knowlton et al. 1990; Pauly 1995; Aronson and Precht 2001b; Jackson et al. 2014). More importantly, a general lack of temporal (short- and long-term) information on the presence/status of individual coral species makes it difficult to identify species responses to environmental change and/or anthropogenic stress, and whether these responses can be predictable (Darling et al. 2012).

In the last 40 years three major events have produced substantial coral mortalities with different degrees of coral community changes around the Caribbean. All three were associated with mild to strong elevated thermal anomalies linked to global climate change. These include the disease-induced massive mortalities of the branching acroporids and the sea urchin *Diadema* in the early 1980's, and the disease- and bleaching-induced mass mortalities of the massive reef-building, foundational coral species (i.e., *Orbicella* species complex; *Pseudodiploria* spp., *Diploria* sp., *Siderastrea* spp., *Colpophyllia* spp. etc.) in the early 2000's in the northern Caribbean and in 2010 in the southern Caribbean (Weil et al. 2009a; Rogers et al. 2008; Weil and Rogers 2011; Bastidas et al. 2012). These events were compounded by hurricanes and a wide range of local and regional impacts related to explosive human population growth, overfishing, coastal development, sedimentation, pollution, and invasive species (Weil et al. 2003, 2009a; Rogers et al. 2009; Weil and Rogers 2011; Jackson et al. 2014).

The mass mortality of the acroporids in the early 1980's was the first massive mortality of corals recorded for the region and marked a major turn for Caribbean reefs. The collapse of the acroporids resulted in massive losses of live coral, structural complexity, biodiversity, functionality, and ecological services (Lessios et al. 1984; Lessios 2016; Bythell et al. 1993; Wilkinson 2005; Aronson and Precht 2001b; Weil et al. 2002; Gardner et al. 2003; Jackson et al. 2014). There was a significant loss of live coral and an increase in algal cover that have not recovered after nearly 40 years. Gardner et al. (2003) and Jackson et al. (2014) summarized (metadata analyzes) all monitoring data available for the Caribbean and showed that live coral cover declined from an average 50% in the 1970's to 10-15% by 2002, which represented between 70 and 80% of live tissue loss. This dramatic loss was followed by two major thermal warming anomalies (>12 Degree Heating Weeks-NOAA Coral Reef Watch) that induced widespread and severe coral bleaching and disease outbreaks in 2005 and 2010 in the northeastern and south Caribbean respectively. NOAA's Extended Reconstructed SST product showed that average ocean temperatures during the July-October period for the Caribbean in 2005 exceeded temperatures seen at any time during the prior 150 years (Eakin et al. 2010). Puerto Rico and the USVI reported average total losses of 53% and 60% of live coral cover respectively (Miller et al. 2003, 2006, 2009; Weil et al. 2009a). The significant declines of some reef-building species in PR and USVI, combined with similar declines on the Florida Reef Tract, prompted the listing of several foundational species, such as the acroporids, the *Orbicella* species complex, and the pillar coral *Dendrogyra cylindrus,* as threatened under the United States Endangered Species Act (71 FR 26852–26861; 79 FR 53851).

While global ocean warming intensifies and thermal anomalies become more frequent, intensive and extensive bleaching and disease outbreaks will continue to occur (Hughes et al. 2018). During their long evolutionary history, coral reefs have recovered, expanded and persisted when relatively good and constant environmental conditions were present. Currently, coral recovery is imperiled by the high number of distinct disturbances and multiple stressors acting concurrently and/or in synergy that cause coral mortality. There has been a lack of high-quality environmental conditions that would allow even partially recovery. The pattern and mode of reproduction, fertilization success, larval dispersal, recruitment, and juvenile survivorship determine population and coral community fitness for these foundational taxa and other important organisms (Szmant 1986; Edmunds 2005; Van Oppen et al. 2002; Vermeij et al. 2003; Vermeij 2006; Harrison 2011). Each process is critical to maintaining healthy coral population dynamics and the regeneration of healthy coral reef communities (Harrison and Wallace 1990; Vermeij 2005; Weil et al. 2009b; Harrison 2011). Recurrent recruitment failure, lower fecundities, and low reproductive output for scleractinian corals have been attributed as major factors explaining why impacted reefs are not recovering from recent mass mortalities (Hughes and Connell 1999; Hughes and Tanner 2000).

Puerto Rico and the USVI

As in many other Caribbean islands, coral reef ecosystems in the USVI and Puerto Rico include a mosaic of different habitats, structures and communities (i.e., coral, octocoral, hydrocoral, crustose coralline algae reefs, seagrasses, soft bottom communities, and mangrove forests). They all vary in structural complexity, biomass, productivity, and biodiversity; but they have strong dependencies on the flow of resources and energy. These biologically rich communities provide important ecosystem services such as shoreline protection and support valuable socio-economic activities (e.g., fishing and tourism).

In both USVI and Puerto Rico island complexes, coral reefs are mostly found as fringing, bank, patch, and spur and groove formations distributed near-shore, along the insular platforms and at the shelf-edge of the island platform down to 60-70 m (Almy and Carrión-Torres 1963; Goenaga and Cintrón 1979; Ogden 1980; Beets et al. 1986; García-Sais et al. 2003, 2005, 2008; Rogers et al. 2008; Ballantine et al. 2008). However, Randall (1961) referenced the presence of a barrier reef while making recommendations to recognize Buck Island in St. Croix as a National Monument and stated that "*The barrier reef is undoubtedly the most magnificent coral reef in the possession of the United States and deserving of protection from the depredations of man. The broad beach at the west end and placid, clear lagoon have excellent recreational potentiality.*

Colonies of pelican and frigate birds and sea turtles are in need of protection". "Fringing and bank coral reefs are the most common. These are located throughout most of the northeast, east, south and southwestern coastlines associated with erosional consolidated rocky features of the shelf". In most instances, coral is not the main constituent of the basic reef structure, but its development has significantly contributed to topographic relief, influencing the sedimentation of adjacent areas and providing habitat for a taxonomically diverse community that is consistent with a coral reef system (García-Sais et al. 2003, 2005). The geology of these two groups of islands is different and has been well described (Adey et al. 1977; Hubbard et al. 1997, 2008; Acevedo and Morelock 1988; Mann 2005). Modern shelf-edge reefs formed in Puerto Rico and the USVI some 8,000 years ago (Adey 1978) (Table 1).

The USVI in the northeastern Caribbean, consist of St. Croix (207 km^2), St. Thomas (83 km^2), St. John (52 km^2) and numerous smaller islands (Dammann and Nellis 1992). An extensive platform underlies St. Thomas and St. John and connects these islands to Puerto Rico and the British Virgin Islands. St. Croix, St. Thomas, and St. John have 113, 85 and 80 km of shoreline, respectively. The most developed reefs in general, are found off the eastern, windward ends of the islands. Estimates of the spatial extent of coral reef ecosystems from Landsat satellite imagery for the USVI indicate that coral reef ecosystems cover approximately 344 km^2 (down to 18 m depth) or 2,126 km^2 (down to 183 m depth) (Rohmann et al. 2005) (Table 1). Puerto Rico, the easternmost island (18°15′ N and 66°30′ W) of the Greater Antilles, is about 50 km wide and 180 km long on its east/west axis and has a coastline of 1,384 km including the adjacent islands of Vieques, Culebra, Desecheo, and Mona. Recent mapping by NOAA of the coastal ecosystems and associated habitats of Puerto Rico indicate that coral reefs and hard bottom habitats comprise about 757 km^2 (15.1%), seagrass meadows 625 km^2 (12.8%), macro algal dominated hard bottom 97 km^2 (1.9%) and mangrove fringes and forests covered 73 km^2 (1.9%).

Table E1. Geographic/Disturbance Information. The impacting hurricane category includes all hurricanes and tropical storms to impact Puerto Rico and the USVI since 1780 (deadliest hurricane on record (San Calixto) caused over 27,000 deaths along the Lesser Antilles and Dominican Republic). Thermal anomalies include those with a temperature accumulation of more than 6 degree-heating weeks (Eakin et al. 2010) (6 consecutive weeks with water temperatures 1°C above the historical average for seasons: 2005, 2010, and 2019) that produced extensive bleaching.

Parameter	**USVI**	**Puerto Rico**
Coastal length	378 km	1,087 km
Land area	370 km^2	9,000 km^2
Maritime area	5,894 km^2	204,942 km^2
Population	101,328	3,940,410
Reef areas	134 km^2	471 km^2
Impacting Hurricanes	36 (From 1780 until 2018)	58 (From 1780 until 2018)
Thermal anomalies	6 (1987, 1998, 1999, 2005, 2010, 2019)	5 (1969, 1998, 2003, 2005, 2010)
Extensive bleaching	6 (1987, 1998, 1999, 2005, 2010, 2019)	5 (1998, 2003, 2005, 2010, 2019)
Deadly disease outbreaks	6	8
Type of disease	WBD, WPD, CYBD, ASP, *D. antillarum,*	BBD, WBD, WPD, CYBD, ASP,

	SCTLD	*D. antillarum,* GWD, SCTLD

WBD= white band disease; WPD= white plague disease; CYBD= Caribbean yellow band disease; ASP= aspergillosis; *D. antillarum*= mass mortalities of the urchins; GWD= *Gorgonia* waste disease; SCTLD= Stony coral tissue loss disease.

There is very limited quantitative information for coral reef communities in USVI and PR before 1890. It was not until 1898, with the *Fish Hawk* expedition that the first organized scientific study targeting Puerto Rico's coral reefs occurred, including the first *in situ* reef descriptions. Reefs off the Mayagüez area on the west coast were reported to consist primarily of *Acropora palmata* and *A. cervicornis* mixed with brain corals *(Pseudodiploria strigosa*), and patches of octocorals (*Pseudopterogorgia acerosa* and *Gorgonia ventalina*), the hydrocoral, *Millepora alcicornis*, and in the interstices of the reef were starfishes, crustaceans, and the black sea urchin *D. antillarum*. Elkhorn coral (*A. palmata*) was reported to grow close to the surface to 1–3 m deep with large stands in several areas exposed at low tide (Evermann 1900). This report clearly describes structurally complex, highly diverse, and healthy reefs dominated by acroporids in areas where today, all that remains are dead skeletons, rubble, sediment, and algae-covered consolidated limestone.

Have other healthy coral reef areas suffered the same fate after the development of coastal towns, ports, and petro-chemical processing industries that caused overfishing and deforestation? Reefs in Puerto Rico have shown a marked loss of living coral during the past three decades. According to Morelock et al. (2001), "*Rapid rates of human population growth and density in Puerto Rico, have led to increased deforestation for agriculture and increased discharge of sewage and industrial waste*". According to the State of Coral Reef Ecosystems report (Turgeon et al. 2002), anthropogenic stressors affecting reefs off urbanized areas in Puerto Rico originated from human activities initiated during the 1950s - for example massive clearing of mangrove forests, runoff from large scale agricultural developments, and construction of thermo-electrical plants on the north and south coasts - to ship groundings, especially those occurring during the 1980's and 1990's. Some of the consequences associated with increased human modifications include high terrigenous sediment influx, increased nutrient levels, overfishing, and extensive habitat modification.

In Puerto Rico coral reefs fringe many small islands or cays along the south coast. In some instances, coral growth has been primarily responsible for the formation of these small cays and other emergent islands, such as the mangrove and coral cays off La Parguera Natural Reserve (LPNR), considered to be the best coral reef development in Puerto Rico (García-Sais and Sabater 2004; Ballantine et al. 2008). Some fringing reefs are also found off the northeast coast, mostly on the leeward section of the islands off Fajardo (in the Cordillera de Fajardo Natural Reserve), Culebra, and Vieques. Most of the north shores are exposed to the Atlantic, with narrow consolidated limestone fringes on top of a short platform that drops rapidly to mesophotic depths and into the Puerto Rico Trench. All major rivers of Puerto Rico discharge along the north coast, contributing large amounts of sediments, and lowering visibility and salinity (Ballantine et al. 2008). In Puerto Rico, reefs with the highest live coral cover are generally found: at the leeward side of the island (Desecheo, Mona); at offshore islands on the eastern, windward side (Vieques, Culebra, Cayo Diablo); and associated with the mainland shelf-edge in the south (Derrumbadero), southwest (La Boya Vieja and Weimberg) and west coast (Tourmaline). Boulder star coral, the *Orbicella annularis* species complex, is generally the dominant coral species by substrate cover on reefs with relatively high coral cover. *Montastraea cavernosa, Siderastrea siderea* and *Porites astreoides* constitute the main coral populations of degraded reefs communities (Ballantine et al. 2008; García-Sais et al. 2008).

Most fringing, windward, exposed reefs around Puerto Rico and the USVI were formed by extensive stands and thickets of *A. palmata* and *A. cervicornis*. *Diadema antillarum*, one of the most important herbivores in the region's coral reefs, was very abundant in the USVI and Puerto Rico until 1983 (Ogden et al. 1973; Levitan 1988; Weil et al. 2002, 2005; Tuohy et al. 2020). This reef scape changed significantly after the acroporid and the *Diadema* mortalities in the early 1980's, which resulted in increased turf- and macro-algae as coral populations endured major losses in live tissues, structural complexity, and biodiversity, with cascading consequences affecting their functionality and most likely, other important ecological services (Gladfelter 1982; Goenaga and Boulon 1992; Bruckner and Bruckner 1997a, b; Williams et al. 1999; Weil et al. 2002; Weil and Rogers 2011). Reefs continued to decline slowly, following mild bleaching events associated with mild thermal anomalies in 1987, 1990, 1998, 1999, and 2003. Up to 90% of coral species were affected, but no significant coral mortality was observed (Weil et al. 2002, 2009a; NPS 2019; Resource Brief. National Park Service. https://irma.nps.gov/Datastore/Reference/Profile/2271606.)

Local disease outbreaks (black band disease (BBD), white plague disease (WPD), aspergillosis (ASP), dark spots disease (DSD), and Caribbean yellow band disease (CYBD)) seem to be associated with these thermal anomalies since they occurred during the summer and through the fall following the bleaching events. The deadly CYBD was observed for the first time in 1998 and every following year with prevalence values varying seasonally but steadily increasing on reefs of Southwest Puerto Rico, Desecheo and Mona Islands (Bruckner and Bruckner 2006; Harvell et al. 2009; Weil et la. 2009a, b; Bruckner and Hill 2009). Other impacts from hurricanes, sedimentation, algal overgrowth, overfishing, snail predation, and extensive decline in water quality, contributed to local mortalities and deterioration of these important communities (Rogers et al. 1988, 2009; Rogers 1990; Bruckner and Bruckner 2003; Ballantine et al. 2008; Weil et al. 2009a). In 2005-2006, the north-eastern Caribbean was exposed to the longest high thermal anomaly (14 degree-heating weeks) that induced the most intensive bleaching event in recorded history (McClanahan et al. 2009; 2018; Eakin et al, 2010), triggering new, widespread outbreaks of WPD in both Puerto Rico and the USVI, increasing virulence and prevalence of CYBD, and outbreaks of other diseases affecting octocorals and crustose coralline algae.

Up to 80% bleaching prevalence was observed in several reefs Puerto Rico during 2005 and 2010, with more than 90 cnidarian species affected. Five species of hydrocorals (100% of the species pool), 60 species of scleractinians (90% of the species pool), and 30 octocoral species

(20% of the species pool) bleached along with other cnidarians and sponges (García-Sais et al., 2006; McClanahan et al. 2009, 2018; Prada et al. 2010). Individual species and community-level disease prevalence, incidence, virulence, and mortality varied significantly both spatially and temporarily in the different localities. Coral community level disease prevalence reached 32% in the Spring-Summer of 2006 in Southwest Puerto Rico, with some foundational species showing up to 50% of their colonies with disease signs (Weil et al. 2009a). Overall, between 53% and 60% tissue loss was estimated at the coral community level over a few of years in Puerto Rico and the USVI, most of this caused by disease rather than bleaching outbreaks (Miller et al. 2009; Rogers et al. 2009; Weil et al. 2009a).

Declines in live coral cover in the USVI from the late 1970's to early 2011 indicates significant losses ranging from 4% to 60% of the original live cover over time (Smith et al. 2001, 2010; Miller et al. 2006, 2009; Edmunds and Elahi 2007; Rogers et al. 2008, 2009; Jackson et al. 2014). Table 5 in Jackson et al. (2014) shows mean coral cover to be 23.7% in St. Croix, 34.1% in St. John and 32.5% in St. Thomas from 1970 to 1983; followed by 20.7%, 26.1% and 4.6% respectively from 1984 to 1998; and 9%, 11.8% and 13.9% respectively from 1999 to 2011. This represents proportional live cover losses of 62%, 65%, and 57% respectively from 1970 to 2011 (Tsounis and Edmunds 2017), mostly attributed to the *Acropora*/*Diadema* die-offs in the early 1980's, and the massive coral species mortalities between 2003 and 2007 (Miller et al. 2006, 2009). Live coral cover stabilized after 2011 and even increased in some well monitored localities, but it has not recovered to pre-1980's levels (Goenaga and Boulon 1992; Edmunds 2002; Weil et al. 2002; Gardner et al. 2003; Rogers et al. 2009; Jackson et al 2014; South Florida/Caribbean Network Coral Reef Monitoring 2019 https://irma.nps.gov/Datastore/Reference/Profile/2271606).

For Puerto Rico, the net loss of 70% of live coral referenced in the literature between 1970 and 1984 was only available from Vieques. This high mortality reflected the disappearance of acroporids. This was probably the fate of most shallow and intermediate (1 to 10 m deep) reef communities around Puerto Rico and adjacent islands during that time, when acroporids were dominant and the primary builders of the complex shallow reef framework. Even the Mayagüez bay reefs, close to the mouth of the Yaguez River, had well developed acroporid communities in the late 1800's (Evermann 1900). Similar declines occurred at other localities around the Caribbean (Jamaica, Curacao, Caymans, etc.) with the major proportional decline in live coral cover occurring from 1970 to 1984 as a consequence of WBD epizootic around the Caribbean causing the regional disappearance of acroporids (Gardner 2003; Jackson et al 2014). Overfishing of herbivorous fish and the *Diadema antillarum* mortality compounded these effects by allowing algae to colonize and compete for space, and in many places overgrowing and killing corals (Knowlton et al. 1990).

Even though a loss of 13% coral cover was reported for Vieques between 1994 and 2011, most reefs in Fajardo (Culebra), and the south, south-west coast, and Desecheo and Mona islands probably had significantly higher losses of live coral cover between 1994 and 2011. Culebra and

LPNR loss between 60% and 53% respectively, mostly related to disease and the 2005-2006 increased temperature-induced bleaching and subsequent new epizootic events that caused widespread coral and octocoral mortalities (Hernandez-Delgado et al. 2006, 2010; Weil et al. 2009a; Prada et al. 2010; Jackson et al 2014). There has not been significant recovery on reefs since 2007, so current live coral cover is ranging between 4% and 32 % for the USVI and Puerto Rico respectively (Weil et al. 2009a; Miller et al. 2009; Jackson et al. 2014; Smith et al. 2015; García-Saiset al. 2017; South Florida/Caribbean Network Coral Reef Monitoring in US Virgin Islands National Park 2019 https://irma.nps.gov/Datastore/Reference /Profile/2271606; Figuerola et al. 2020). It is also important to keep in mind that variability in live coral cover (percentage), composition and structure of coral reefs, as well as their response to different stressors could be significant even at small spatial scales (hundreds of meters).

Several coral reef assessments in both the USVI and Puerto Rico over the years have provided a broad overview of the continuous overall decline in coral cover (with short periods showing increases in coral cover), current community characteristics, and the status of change of coral reef ecosystems, which lead to recommendations for implementation and enforcement of existing and new regulations to protect these communities (Catanzaro et al. 2002; García-Saiset al. 2004, 2005, 2006; 2008; Miller et al. 2006; Rogers et al. 2008, 2009; Rogers and Miller 2016; Rothenberger et al. 2008; Tsounis and Edmunds 2017; South Florida/Caribbean Network. 2019. Coral Reef Monitoring in US Virgin Islands National Park, Buck Island and Salt River 2019 https://irma.nps.gov/Datastore/Reference /Profile/2271606).

Conceptual considerations to characterize BCG Condition Level 1 for fore reef habitats in Puerto Rico and the USVI.

The standard definition for BCG condition Level 1 framework states "*Biological conditions as they existed (or still exist) in the absence of measurable effects of stressors and provides the basis for comparison to the next five levels*" (EPA 2016). This definition can be complemented with concepts of biodiversity and ecosystem function which provides a conceptual basis to model a healthy, stable, functional community. The two most important biological components are the structure (the overall biodiversity) and the functionality defined by the flux of energy and resources throughout the community (nutrient recycling, recruitment, productivity, herbivory, reef accretion, growth of corals and other key organisms, etc.,) that could be reflected as the resistance to change (stability of the structure, composition, and functionality over time), and the capacity to recover after a disturbance (resilience).

The BCG Level 1 characterization for biological condition will benefit from inclusion of properties for reef conditions and traits scientists believed were present in the northern and northeastern Caribbean reefs before the major disturbances discussed above significantly changed the region's coral reef landscape to the present. A fully functional and intact BCG Level 1 reef should not just be considered as a structure, but also include components to show it is a functioning ecosystem with all processes intact. The duration of current local or regional, favorable environmental conditions for "reef development" are probably too short to allow for the recovery of most coral reef foundational taxa because of the intrinsic life-history characteristics of these long-lived, slow growing organisms. Significant disturbances such as bleaching, diseases, storms and pollution are occurring more frequently and with higher intensity, continuously disrupting and eliminating any positive advances in the ecological successional process, thus disguising that baseline that keeps eluding us.

Back in the late 1970's for example, many fore reefs probably did not have any significant acroporid populations and were not affected by the WBD epizootic in the early 1980's. However, they were most probably impacted by the emergence of the many new diseases affecting the most foundational, massive species. Black band disease affected most boulder and massive species since the early 1970's (Antonious 1973; Rutzler et al 1983), and it was followed by other localized outbreaks (WPD, CYBD, bleaching) until the significant outbreaks of the early-mid 2000'. The combination of highly prevalent diseases together with intense bleaching events produced significant mortalities across the region, including Puerto Rico and the USVI. Coral reef structural complexity collapsed, decreasing biodiversity, productivity, trophic networks, ecological redundancy, reproductive output, and ecosystem functionality; vital reef processes that were impacted over many years in the future.

High coral cover of a single, dominant species is usually only characteristic of extreme habitats, like *A. palmata* dominating shallow exposed frontal reef areas, *P. porites* monopolizing extensive back reef areas, or *A. cervicornis* in protected lagoon reef environments. Recovery of these kinds of habitats might occur faster depending on availability and survival of recruits for fast growing, weedy species. These species can easily monopolize extensive areas of reef substrate with favorable environmental conditions that exist for shorter times compared to those that need stable environmental conditions lasting for long periods, optimal for highly diverse communities with slow-growing, massive species.

Species diversity can vary substantially from reef to reef, or even habitat-to-habitat within the same reef. Although not recorded in the literature, local observations of the demise and decline of highly abundant taxa such as *Acropora* spp., *Millepora* spp., and less common species such *Scolymia cubensis*, *Millepora squarrosa*, *Isophyllia* spp., and *D. cylindrus* in the last 20-30 years, support assumptions that perhaps hundreds or thousands of other invertebrate species and microorganisms associated with coral reefs became locally or regionally extinct. Overall, the loss of biodiversity was significant, affecting the community functionality (fluxes of energy and resources; microorganisms providing essential nutrients recycling), with a cascade of detrimental ecological consequences that ensued thereafter. Due to the variety of concurrent and synergistic detrimental factors (disturbances) still in progress, neither of these important community components seem to have recovered to pre-1980's conditions. Moreover, since the foundational and most important species of coral reefs are modular, slow growing, long-lived taxa, recovery if any, could take a long time even under the best of conditions.

Appendix M – Coral Species Attribute Assignments Made by Professional Judgment of Coral Reef Experts

Sediment tolerance was used as a surrogate for landscape stressors and elevated heat tolerance as a proxy for climate change stressors. The expected density at single site (distribution within a site) and frequency of occurrence (distribution among sites) were ranked from low to high.

Scientific Name	Common English Name	BCG Attribute	BCG Sediment Attribute	BCG Heat Attribute
Acropora cervicornis	Staghorn coral	3	3	3
Acropora palmata	Elkhorn coral	4	4	3
Acropora prolifera	Fused staghorn	4	4	3
Agaricia agaricites	Lettuce coral	4	4	2
Agaricia fragilis	Fragile saucer coral	NA		
Agaricia grahamae	Dimpled sheet coral	NA		
Agaricia humilis	Low relief lettuce coral	4	4	2
Agaricia lamarcki	Whitestar sheet coral	3	3	2
Agaricia spp		NA		
Agaricia tenuifolia		NA		
Cladocora arbuscula	Tube coral	4	4	4
Colpophyllia natans	Boulder brain coral	3	3	3
Dendrogyra cylindricus	Pillar coral	3	3 4	3
Dichocoenia stokesii	Elliptical star coral	4	4	3
Diploria labyrinthiformis	Grooved brain coral	3	3	3
Diploria spp		NA		
Eusmilia fastigiata	Smooth flower coral	3	3	3
Favia fragum	Golf ball coral	5	5	4
Helioseris cucullata		3	3	3
Isophyllastrea rigida	Rough star coral	2	2 ?	2 ?
Isophyllia sinuosa	Sinuous cactus coral	2	2 ?	2 ?
Madracis auretenra	Yellow pencil coral	4	4	3
Madracis decactis	Ten ray star coral	3	2 4	4
Madracis formosa	Eight-ray star coral	NA		
Madracis pharensis		NA		
Madracis senaria	Six-ray star coral	NA		
Madracis spp		NA		
Manicina areolata	Rose coral	5	5	5
Meandrina danae	Butterprint rose coral	NA		
Meandrina jacksoni	White valley maze coral	4	4	3
Meandrina meandrites	Maze coral	4	4	3
Meandrina spp		NA		
Millepora alcicornis	Branching fire hydrocoral	5	5	2

Scientific Name	Common English Name	BCG Attribute	BCG Sediment Attribute	BCG Heat Attribute
Millepora complanata	Blade fire hydrocoral	3	3	2
Millepora spp		NA		
Millepora squarrosa	Box fire hydrocoral	NA		2
Montastraea cavernosa	Great star coral	5	5	4 5
Mussa angulosa	Atlantic mushroom coral	4	4	2
Mycetophyllia aliciae	Knobby cactus coral	4	4	3
Mycetophyllia daniana	Low ridge cactus coral	NA		
Mycetophyllia ferox	Rough cactus coral	4	4	2 3
Mycetophyllia lamarckiana	Ridged cactus coral	NA		
Mycetophyllia reesi		NA		
Mycetophyllia spp	Cactus coral	NA		
Oculina diffusa	Diffuse ivory coral	5	5	4
Orbicella annularis	Lobed star coral	4	4	2
Orbicella annularis complex		4		
Orbicella faveolata	Mountainous star coral	4	4	2
Orbicella franksi	Boulder star coral	4	4	2
Orbicella spp		4		
Porites astreoides	Mustard hill coral	5	5	5
Porites branneri	Blue crust coral; porous coral	NA		
Porites colonensis	Honeycomb plate coral	NA		
Porites divaricata	Thin finger coral	5	5	4
Porites furcata	Branching finger coral	4	4	4 5
Porites porites	Clubtip finger coral	4	4	4
Porites spp		4		
Pseudodiploria clivosa	Knobby brain coral	5	5	4
Pseudodiploria strigosa	Symmetrical brain coral	5	5	4
Scleractinia spp	Stony coral	NA		
Scolymia cubensis	Solitary disk corals	4	4	4
Scolymia lacera	Solitary disk corals	4	4	4
Scolymia spp		NA		
Siderastrea radians	Lesser starlet coral	5	5	5
Siderastrea siderea	Massive starlet coral	5	5	4
Siderastrea spp		NA		
Solenastrea bournoni	Smooth star coral	5	5	4
Solenastrea spp		NA		
Stephanocoenia intersepta	Blushing star coral	5	5	4
Tubastraea coccinea	Orange cup coral	6		

Appendix N – Benthic Metrics Used in Developing BCG Rules

Metric	**Description**	**Ecological Rationale**
Percent Coral Cover (LPI)	Percent cover is calculated by dividing the number of points on the LPI survey where stony coral was recorded by the number of total points along the transect	The percentage of the seafloor occupied by living scleractinian corals. Coral cover is related to habitat complexity and is a predictor of fish and invertebrate diversity and abundance (Risk 1972; Luckhurst and Luckhurst 1978; Gladfelter et al. 1980; Bell and Galzin 1984; Friedlander et al. 2003; Jones et al. 2004; Gratwicke and Speight 2005; Idjadi and Edmunds 2006; Alvarez-Filip et al. 2009; Dustan, Doherty and Pardede 2013).
Percent live coral cover (DEMO)	From the DEMO survey; calculated in 2 dimensions based on colony diameter, height, and mortality measures	Stony corals are marine invertebrates that live in colonies of many identical individual soft-bodied polyps. At the base of each polyp is a hard, protective limestone skeleton called a calicle, which connect to other calicles, forming a coral colony that acts as a single organism. Coral colonies are unique in that they can experience partial tissue death and still remain alive. Live coral cover is the primary indicator of the health of coral reefs. Studies have shown a positive relationship between live coral cover and fish diversity or abundance, including abundance of obligate coral-dwelling species and corallivorous fishes (Bell and Galzin 1984; Sano et al. 1984; Bouchon-Navaro and Bouchon 1989; Chabenet et al. 1995; Jones et al. 1997; Syms and Jones 2000; Kokita and Nakazono 2001; Spalding and Jarvis 2002; Pratchett et al. 2006).
Percent live cover of large, reef-building coral (DEMO)	From the DEMO survey	Large Reef-Building Corals (LRBC) include *Orbicella, Acropora, Diploria, Pseudodiploria, Colpophyllia, Dendrogyra, Monteastrea cavernosa,* and *Siderastrea siderea. Orbicella* and *Acropora* are the major reef building coral genera in the Caribbean.
% live *Orbicella* cover (DEMO and LPI)	% cover as calculated from the DEMO or LPI surveys	High *Orbicella* cover was considered a dependable indicator of relatively undisturbed reef conditions (Goreau 1959; Cruz-Piñón et al 2003; Kramer 2003; Oliver et al. 2018).
3-D Live Coral Cover (DEMO)	From the DEMO survey	Calculated in 3 dimensions based on colony diameter, height, morphology, and mortality measures. Rational is as described for Percent Live Coral Cover (DEMO)

Metric	**Description**	**Ecological Rationale**
Total Coral Richness (LPI)	From the LPI survey	Species richness is the number of different species represented in an ecological community, landscape or region. Species richness is simply a count of species, and it does not take into account the abundances of the species or their relative abundance distributions. Coral species richness is correlated with fish species richness. Some coral reef fish are dependent on live coral, juveniles of many fish species prefer to settle near live coral and some fish species exhibit preferences for specific coral species or morphologies (Beukers and Jones 1997; Munday 2001; Holbrook et al. 2002a, b; Jones et al. 2004; Pratchett et al. 2008; Komyakova et al. 2013).
Non-tolerant Coral Richness (DEMO and LPI)	# taxa (both DEMO and LPI)	Number of coral species that have demonstrated or are thought to be sensitive to anthropogenic stressors (BCG Attributes I, II and III).
Density of Colonies (DEMO)	From the DEMO survey	Density is the number of individuals observed per unit area; in the case of coral surveys the unit area is m^2 of seafloor. Coral density characterizes the proximity of colonies to one another—a factor that affects disease transmission, sexual reproduction and recruitment (Fisher 2007).
Density of medium or large colonies (DEMO)	From the DEMO survey	Coral colony size is an important indicator of growth, reproduction, population dynamics and community interactions (Fisher et al. 2007). It takes a long time to grow a large coral colony. Measured as the number of number of colonies with a diameter > 20cm within the transect. Larger colonies indicate stability of coral growing conditions over time (Fisher et al 2008).
Percent coral mortality (DEMO)	From the DEMO survey	Mortality indicates poor individual and community condition (Lirman et al. 2014)
Bare Substrate and Turf with Sediment (LPI)	From the LPI survey	Reef habitat that is not supporting healthy live organisms indicates that the reef is either patchy or unable to sustain a growing benthic assemblage.

Appendix O – Fish Species Attribute Assignments Made by Professional Judgment of Coral Reef Experts

Notes: (1) Assigned attributes are based upon sensitivity to fishing pressure and sediment stress and apply to the entire US Caribbean unless otherwise noted in Column (2) Florida Assigned Attribute; 3) Abbreviations for the trophic guilds are: H= herbivore, P = piscivores, I =invertivore, and Z = zooplanktonivore

Assigned Attribute (1)	FL Assigned Attribute (2)	Species Name	Common Name	Guild (Caldow 2009)	Large (LP) or Small Piscivore (SP)
Attribute I: Historically documented, sensitive, long-lived, or regionally endemic taxa					
I		*Acanthostracion polygonius*	Honeycomb cowfish	I	
I		*Acanthostracion quadricomis*	Scrawled cowfish	I	
I		*Carcharhinus limbatus*	Blacktip shark	P	LP
I		*Carcharhinus perezii*	Caribbean reef shark	P	LP
I		*Epinephelus itajara*	Atlantic Goliath Grouper	P	LP
I		*Epinephelus morio*	Red grouper	I	
I		*Epinephelus striatus*	Nassau grouper	P	LP
I		*Mycteroperca bonaci*	Black grouper	P	LP
I		*Mycteroperca interstitialis*	Yellowmouth grouper	P	SP
I		*Mycteroperca tigris*	Tiger grouper	P	LP
I		*Mycteroperca venenosa*	Yellowfin grouper	P	LP
I		*Scarus coelestinus*	Midnight parrotfish	H	
I		*Scarus coeruleus*	Blue parrotfish	H	
I		*Scarus guacamaia*	Rainbow parrotfish	H	
I		*Sphyrna mokarran*	Great Hammerhead Shark	P	LP
Attribute II: Highly sensitive taxa (fishing pressure and sediment stress)					
II		*Aetobatus narinari*	Spotted eagle ray	I	
II		*Aluterus scriptus*	Scrawled filefish	I	
II		*Amblycirrhitus pinos*	Redspotted hawkfish	Z	
II		*Anisotremus surinamensis*	Black margate	I	
II		*Astrapogon stellatus*	Conchfish	I	
II		*Aulostomus maculatus*	Trumpetfish	P	SP
II		*Cantherhines macrocerus*	America whitespotted filefish	I	
II		*Cantherhines pullus*	Orangespotted filefish	H	
II		*Caranx crysos*	Blue runner	P	SP
II		*Caranx hippos*	Crevalle jack	P	LP
II		*Cephalophilus furcifer*	Atlantic creolefish	Z	

Assigned Attribute (1)	FL Assigned Attribute (2)	Species Name	Common Name	Guild (Caldow 2009)	Large (LP) or Small Piscivore (SP)
II		*Chaenopsis limbaughi*	Yellowface pikeblenny	I	
II		*Chaetodipterus faber*	Atlantic spadefish	I	
II		*Chromis cyanea*	Blue chromis	Z	
II		*Chromis multilineata*	Brown chromis	Z	
II		*Clepticus parrae*	Creole wrasse	Z	
II		*Dactylopterus volitans*	Flying gurnard	I	
II		*Dasyatis americana*	Southern stingray	I	
II		*Elacatinus genie*	Cleaner goby	H	
II		*Elacatinus multifasciatus*	Greenbanded goby	I	
II		*Elacatinus oceanops*	Neon goby	I	
II		*Elacatinus prochilos*	Broadstripe goby	I	
II		*Elacatinus saucrum*	Leopard goby	I	
II		*Enchelycore nigricans*	Viper moray	P	SP
II		*Fistularia tabacaria*	Bluespotted cornetfish	P	SP
II		*Galeocerdo cuvier*	Tiger shark	P	LP
II		*Ginglymostoma cirratum*	Nurse shark	P	LP
II		*Gramma loreto*	Fairy basslet	I	
II		*Haemulon chrysargyreum*	Smallmouth grunt	I	
II		*Halichoeres radiatus*	Puddingwife	I	
II		*Heteropriacanthus cruentatus*	Glasseye snapper	Z	
II		*Holacanthus ciliaris*	Queen angelfish	I	
II		*Holacanthus tricolor*	Rock beauty	I	
II		*Hypoplectrus gemma*	Blue hamlet		
II		*Hypoplectrus hybrid*	Hybrid hamlet		
II		*Lachnolaimus maximus*	Hogfish	I	
II		*Lactophrys triqueter*	Smooth trunkfish	I	
II		*Lactophrys bicaudalis*	Spotted trunkfish	I	
II		*Lactophrys trigonus*	Trunkfish	I	
II		*Lutjanus analis*	Mutton snapper	I	
II		*Lutjanus cyanopterus*	Cubera snapper	P	LP
II		*Lutjanus jocu*	Dog snapper	P	LP
II		*Melichthys niger*	Black durgon	H	
II		*Negaprion brevirostris*	Lemon Shark	P	LP
II		*Pareques acuminatus*	Highhat	I	
II		*Priacanthus arenatus*	Bigeye	I	

Assigned Attribute (1)	FL Assigned Attribute (2)	Species Name	Common Name	Guild (Caldow 2009)	Large (LP) or Small Piscivore (SP)
II		*Priolepis hipoliti*	Rusty goby	I	
II		*Prognathodes aculeatus*	Longsnout butterflyfish	I	
II		*Scomberomorus regalis*	Cero	P	SP
II		*Seriola dumerili*	Greater amberjack	P	LP
II		*Seriola rivoliana*	Almaco jack	P	LP
II		*Serranus tigrinus*	Harlequin bass	I	
II		*Thalassoma bifasciatum*	Bluehead	I	
II		*Trachinotus falcatus*	Permit	I	
II		*Trachinotus goodei*	Palometa	P	SP
II		*Xanthichthys ringens*	Sargassum triggerfish	Z	
Attribute III: Intermediate sensitive taxa (fishing pressure and sediment stress)					
III		*Abudefduf taurus*	Night sergeant	H	
III	*x*	*Acanthemblemaria aspera*	Roughhead blenny	I	
III		*Acanthemblemaria maria*	Secretary blenny	I	
III		*Acanthemblemaria spinosa*	Spinyhead blenny	I	
III		*Acanthurus chirurgus*	Doctorfish	H	
III		*Acanthurus coeruleus*	Blue tang	H	
III		*Acanthurus tractus*	Ocean surgeonfish	H	
III		*Apogon aurolineatus*	Bridle cardinalfish	Z	
III		*Apogon binotatus*	Barred cardinalfish	Z	
III		*Apogon lachneri*	Whitestar cardinalfish	Z	
III		*Apogon quadrisquamatus*	Sawcheek cardinalfish	Z	
III		*Astrapogon puncticulatus*	Blackfin cardinalfish	I	
III		*Balistes vetula*	Queen triggerfish	I	
III		*Bodianus pulchellus*	Spotfin hogfish	I	
III		*Bodianus rufus*	Spanish hogfish	I	
III		*Canthidermis sufflamen*	Ocean triggerfish	I	
III		*Caranx latus*	Horse-Eye jack	P	SP
III		*Caranx lugubris*	Black jack	P	LP
III		*Centropomus undecimalis*	Common snook	P	SP
III		*Centropyge aurantonotus*	Flameback angelfish	H	
III		*Cephalopholis cruentata*	Graysby	P	SP
III		*Cephalopholis fulva*	Coney	P	SP
III		*Chaetodon capistratus*	Foureye butterflyfish	I	
III		*Chaetodon ocellatus*	Spotfin butterflyfish	I	

Assigned Attribute (1)	FL Assigned Attribute (2)	Species Name	Common Name	Guild (Caldow 2009)	Large (LP) or Small Piscivore (SP)
III		*Chaetodon striatus*	Banded butterflyfish	I	
III		*Chilomycterus antennatus*	Bridled burrfish	I	
III		*Chromis insolata*	Sunshinefish	Z	
III	x	*Coryphopterus dicrus*	Colon goby	I	
III	x	*Coryphopterus eidolon*	Pallid goby	I	
III		*Coryphopterus lipernes*	Peppermint goby	I	
III		*Cosmocampus elucens*	Shortfin pipefish	I	
III		*Diodon holocanthus*	Balloonfish	I	
III		*Echidna catenata*	Chain moray	I	
III		*Elacatinus chancei*	Shortstripe goby	I	
III		*Elacatinus louisae*	Spotlight goby	I	
III		*Emmelichthyops atlanticus*	Bonnetmouth	P	SP
III		*Epinephelus adscensionis*	Rock hind	I	
III		*Epinephelus guttatus*	Red hind	P	SP
III		*Equetus lanceolatus*	Jackknife fish	I	
III		*Equetus punctatus*	Spotted drum	I	
III		*Gymnothorax miliaris*	Goldentail moray	P	SP
III		*Gymnothorax vicinus*	Purplemouth moray	P	SP
III		*Haemulon album*	Margate (White)	I	
III		*Haemulon carbonarium*	Caesar grunt	I	
III		*Haemulon flavolineatum*	French grunt	I	
III		*Haemulon macrostomum*	Spanish grunt	I	
III		*Haemulon parra*	Sailors choice	I	
III		*Halichoeres garnoti*	Yellowhead wrasse	I	
III		*Halichoeres maculipinna*	Clown wrasse	I	
III		*Halichoeres pictus*	Rainbow wrasse	I	
III		*Hippocampus reidi*	Longsnout seahorse	I	
III		*Holocentrus adscensionis*	Squirrelfish	I	
III		*Holocentrus rufus*	Longspine squirrelfish	I	
III		*Hypoplectrus aberrans*	Yellowbelly hamlet	I	
III		*Hypoplectrus chlorurus*	Yellowtail hamlet	I	
III		*Hypoplectrus guttavarius*	Shy hamlet	I	
III		*Hypoplectrus indigo*	Indigo hamlet	I	
III		*Hypoplectrus nigricans*	Black hamlet	P	SP
III		*Hypoplectrus puella*	Barred hamlet	I	

Assigned Attribute (1)	FL Assigned Attribute (2)	Species Name	Common Name	Guild (Caldow 2009)	Large (LP) or Small Piscivore (SP)
III		*Hypoplectrus randallorum*	Tan hamlet	I	
III		*Hypoplectrus unicolor*	Butter hamlet	P	SP
III		*Kyphosus sectator*	Chub (Bermuda/Yellow)	H	
III		*Labrisomus nuchipinnis*	Hairy blenny	I	
III		*Liopropoma rubre*	Peppermint basslet	I	
III		*Lutjanus buccanella*	Blackfin snapper	P	SP
III		*Lutjanus mahogoni*	Mahogany snapper	P	SP
III		*Lutjanus synagris*	Lane snapper	P	SP
III		*Malacanthus plumieri*	Sand tilefish	I	
III	x	*Malacoctenus aurolineatus*	Goldline blenny	I	
III	x	*Malacoctenus macropus*	Rosy blenny	I	
III		*Malacoctenus versicolor*	Barfin blenny	I	
III		*Megalops atlanticus*	Tarpon	P	LP
III		*Microspathodon chrysurus*	Yellowtail damselfish	H	
III		*Monacanthus ciliatus*	Fringed filefish	H	
III		*Monacanthus tuckeri*	Slender filefish	Z	
III		*Mulloidichthys martinicus*	Yellow goatfish	I	
III		*Myrichthys breviceps*	Sharptail eel	I	
III		*Myrichthys ocellatus*	Goldspotted eel	I	
III		*Myripristis jacobus*	Blackbar soldierfish	I	
III		*Neonifon marianus*	Longjaw squirrelfish	I	
III		*Odontoscion dentex*	Reef croaker	Z	
III		*Ophichthus ophis*	Spotted snake eel	P	SP
III		*Opistognathus aurifrons*	Yellowhead jawfish	Z	
III		*Opistognathus macrognathus*	Banded jawfish	I	
III		*Opistognathus whitehursti*	Dusky jawfish	I	
III	x	*Parablennius marmoreus*	Seaweed blenny	Z	
III		*Pempheris schomburgkii*	Glassy sweeper	I	
III		*Pomacanthus arcuatus*	Gray angelfish	I	
III		*Pomacanthus paru*	French angelfish	I	
III		*Pseudupeneus maculatus*	Spotted goatfish	I	
III		*Rypticus saponaceus*	Greater soapfish		
III		*Sargocentron bullisi*	Deepwater squirrelfish	I	
III		*Sargocentron coruscum*	Reef squirrelfish	I	
III		*Scarus iseri*	Striped parrotfish	H	

Assigned Attribute (1)	FL Assigned Attribute (2)	Species Name	Common Name	Guild (Caldow 2009)	Large (LP) or Small Piscivore (SP)
III		*Scarus taeniopterus*	Princess parrotfish	H	
III		*Scarus vetula*	Queen parrotfish	H	
III		*Scomberomorus cavalla*	King mackerel		
III		*Scomberomorus maculatus*	Spanish mackerel		
III		*Scorpaena plumieri*	Spotted scorpionfish	I	
III		*Selar crumenophthalmus*	Bigeye scad	P	SP
III		*Serranus tabacarius*	Tobaccofish	P	SP
III		*Sparisoma atomarium*	Greenblotch parrotfish	H	
III		*Sparisoma chrysopterum*	Redtail parrotfish	H	
III		*Sparisoma rubripinne*	Yellowtail parrotfish	H	
III		*Sparisoma viride*	Stoplight parrotfish	H	
III		*Sphoeroides spengleri*	Bandtail puffer	I	
III		*Sphyraena barracuda*	Great barracuda	P	LP
III		*Sphyraena picudilla*	Southern sennet	P	SP
III		*Stegastes partitus*	Bicolor damselfish	H	
Attribute IV: Intermediate tolerant taxa (fishing pressure and sediment stress)					
IV		*Abudefduf saxatilis*	Sergeant major	I	
IV		*Alphestes afer*	Mutton hamlet	I	
IV		*Anisotremus virginicus*	Porkfish	I	
IV		*Apogon maculatus*	Flamefish	Z	
IV		*Apogon pseudomaculatus*	Twospot cardinalfish	Z	
IV		*Apogon townsendi*	Belted cardinalfish	Z	
IV		*Archosargus rhomboidalis*	Sea bream	H	
IV		*Bothus lunatus*	Peacock flounder	P	SP
IV		*Bothus ocellatus*	Eyed flounder	P	SP
IV		*Calamus bajonado*	Jolthead porgy	I	
IV		*Calamus calamus*	Saucereye porgy	I	
IV		*Calamus nodosus*	Knobbed porgy	I	
IV		*Calamus penna*	Sheepshead porgy	I	
IV		*Calamus pennatula*	Pluma	I	
IV		*Calamus proridens*	Littlehead porgy		
IV		*Calamus UNK*	Porgy	I	
IV		*Canthigaster rostrata*	Sharpnose puffer	I	
IV		*Carangoides bartholomaei*	Yellow Jack	P	LP
IV		*Carangoides ruber*	Bar jack	P	SP

Assigned Attribute (1)	FL Assigned Attribute (2)	Species Name	Common Name	Guild (Caldow 2009)	Large (LP) or Small Piscivore (SP)
IV		*Chloroscombrus chrysurus*	Atlantic bumper	Z	
IV		*Conger triporiceps*	Manytooth conger	P	SP
IV	x	*Coryphopterus glaucofraenum*	Bridled goby	I	
IV	x	*Coryphopterus personatus/hyalinus*	Masked/Glass goby	I	
IV		*Cryptotomus roseus*	Bluelip parrotfish	H	
IV	x	*Ctenogobius saepepallens*	Dash goby	I	
IV		*Diodon hystrix*	Porcupine fish	I	
IV		*Eucinostomus argenteus*	Spotfin mojarra/Silver mojarra		
IV		*Eucinostomus jonesii*	Slender mojarra	I	
IV		*Eucinostomus melanopterus*	Flagfin mojarra	I	
IV	x	*Gnatholepis thompsoni*	Goldspot goby	H	
IV		*Gymnothorax funebris*	Green moray	P	SP
IV		*Gymnothorax moringa*	Spotted moray	P	SP
IV		*Haemulon aurolineatum*	Tomtate	I	
IV		*Haemulon plumierii*	White grunt	I	
IV		*Haemulon sciurus*	Bluestriped grunt	I	
IV		*Halichoeres bivittatus*	Slippery dick	I	
IV		*Inermia vittata*	Boga	Z	
IV		*Lutjanus apodus*	Schoolmaster	P	SP
IV		*Lutjanus griseus*	Gray snapper	P	SP
IV		*Ocyurus chrysurus*	Yellowtail snapper	Z	
IV	x	*Ophioblennius macclurei*	Redlip blenny	H	
IV		*Paradiplogrammus bairdi*	Lancer dragonet	I	
IV		*Sargocentron vexillarium*	Dusky squirrelfish	I	
IV		*Serranus baldwini*	Lantern bass	I	
IV		*Serranus flaviventris*	Twinspot bass	P	SP
IV		*Serranus tortugarum*	Chalk bass	Z	
IV		*Sparisoma aurofrenatum*	Redband parrotfish	H	
IV		*Sparisoma radians*	Bucktooth parrotfish	H	
IV		*Stegastes adustus*	Dusky damselfish	H	
IV		*Stegastes diencaeus*	Longfin damselfish	H	
IV		*Stegastes leucostictus*	Beaugregory	H	
IV		*Stegastes planifrons*	Threespot damselfish	I	
IV		*Stegastes variabilis*	Cocoa damselfish	H	

Assigned Attribute (1)	FL Assigned Attribute (2)	Species Name	Common Name	Guild (Caldow 2009)	Large (LP) or Small Piscivore (SP)
IV		*Xyrichtys splendens*	Green razorfish	Z	
Attribute V: Tolerant taxa (fishing pressure and sediment stress)					
V		*Diplodus argenteus*	Silver porgy	H	
V		*Gerres cinereus*	Yellowfin mojarra	I	
V		*Mugil cephalus*	Striped mullet	Z	
V		*Sphoeroides testudineus*	Checkered puffer	I	
V		*Synodus foetens*	Inshore lizardfish	P	SP
Attribute VI: Non-native or intentionally introduced species					
VI		*Callogobius clitellus*	Saddled goby	I	
VI		*Pterois volitans*	Red lionfish	P	NA
Attribute x: No attribute assignment (insufficient data); x-MNS – survey method not sufficient to observe actual count; x-UNK – surveyor did not identify down to species; x- NRF – not a reef fish; x-NPR – species not found in Puerto Rico					
x-MNS		*Ablennes hians*	Flat needlefish	P	SP
x-MNS		*Acanthemblemaria UNK*	Tube Blenny	I	
x-NRF		*Acanthocybium solandri*	Wahoo		
x-UNK		*Acanthurus UNK*	Surgeonfish	H	
x-MNS		*Acentronura dendritica*	Pipehorse	I	
x-NRF		*Albula vulpes*	Bonefish	I	
x-NRF		*Alectis ciliaris*	African pompano	P	SP
x-UNK		*Apogon UNK*	Cardinalfish	Z	
x		*Archosargus probatocephalus*	Sheepshead	I	
x-MNS		*Atherinomorus stipes*	Hardhead silverside	Z	
x		*Balistes capriscus*	Gray triggerfish	I	
x-MNS		*Bathygobious soporator*	Frillfin goby	I	
x-UNK		*Belonidae UNK*	Needlefish	P	SP
x-MNS		*Bollmannia boqueronensis*	White-eye goby	I	
x-UNK		*Bothus UNK.*	Flounder	P	SP
x		*Canthigaster jamestyleri*	Goldface toby	I	
x-UNK		*Canthigaster UNK*	Puffer	I	
x		*Carcharhinus leucas*	Bull shark		
x-UNK		*Caranx UNK*	Jack	P	SP
x		*Centropristis striata*	Black sea bass	P	SP
x		*Centropyge argi*	Cherubfish	H	
x-MNS		*Chaenopsis ocellata*	Bluethroat pikeblenny	I	
x-MNS		*Chaenopsis UNK*	Pike blenny	I	
x		*Chaetodon sedentarius*	Reef butterflyfish	I	

Assigned Attribute (1)	FL Assigned Attribute (2)	Species Name	Common Name	Guild (Caldow 2009)	Large (LP) or Small Piscivore (SP)
x		*Chromis enchrysura*	Yellowtail reeffish	I	
x		*Chromis scotti*	Purple reeffish	Z	
x		*Clupeidae UNK*	Herrings	Z	
x-UNK		*Coryphopterus UNK*	Goby	I	
x-MNS		*Coryphopterus punctipectophorus*	Spotted Goby		
x		*Ctenogobius stigmaticus*	Marked goby	I	
x-MNS		*Decapterus macarellus*	Mackerel scad	Z	
x-MNS		*Decapterus punctatus*	Round scad		
x-UNK		*Decapterus UNK*	Scad	Z	
x		*Dermatolepis inermis*	Marbled grouper	P	SP
x		*Diplectrum bivittatum*	Dwarf sand perch	I	
x		*Diplectrum formosum*	Sand perch	P	SP
x		*Diplodus holbrooki*	Spottail pinfish	H	
x-MNS		*Doratonotus megalepis*	Dwarf wrasse	I	
x		*Echeneis naucrates*	Sharksucker	Z	
x		*Echeneis neucratoides*	Whitefin sharksucker	Z	
x-MNS		*Elacatinus dilepis*	Orangesided goby	I	
x-MNS		*Elacatinus evelynae*	Sharknose goby	I	
x-MNS		*Elacatinus horsti*	Yellowline goby		
x-MNS		*Elacatinus macrodon*	Tiger goby		
x-MNS		*Elacatinus UNK*	Goby	I	
x-MNS		*Elacatinus xanthiprora*	Yellowprow goby		
x-MNS		*Elagatis bipinnulata*	Rainbow runner	P	SP
x-MNS		*Emblemaria pandionis*	Sailfin blenny	Z	
x-MNS		*Emblemaria sp*	Tube blenny	Z	
x-MNS		*Emblemariopsis UNK*	Blenny	I	
x-UNK		*Engraulidae UNK*	Anchovies	Z	
x-UNK		*Enneanectes UNK*	Triplefin	H	
x-MNS		*Eucinostomus gula*	Silver jenny	I	
x-UNK		*Eucinostomus UNK*	Mojarra	I	
x-NRF		*Euthynnus alletteratus*	Little tuny	P	SP
x-MNS		*Gobiidae UNK*	Goby	I	
x-MNS		*Gobiosoma grosvenori*	Rockcut goby	I	
x-UNK		*Gymnothorax UNK*	Moray eel	P	SP
x		*Haemulon melanurum*	Cottonwick	I	

Assigned Attribute (1)	FL Assigned Attribute (2)	Species Name	Common Name	Guild (Caldow 2009)	Large (LP) or Small Piscivore (SP)
x-UNK		*Haemulon UNK*	Grunt	I	
x		*Haemulon striatum*	Striped grunt	Z	
x		*Halichoeres burekae*	Mardi gras wrasse	I	
x		*Halichoeres caudalis*	Painted wrasse	I	
x		*Halichoeres cyanocephalus*	Yellowcheek wrasse	I	
x		*Halichoeres poeyi*	Blackear wrasse	I	
x-UNK		*Halichoeres UNK*	Wrasse	I	
x-MNS		*Harengula jaguana*	Scaled sardine		
x-MNS		*Hemiemblemaria simulas*	Wrasse blenny		
x-MNS		*Hemiramphus brasiliensis*	Ballyhoo		
x		*Heteroconger halis*	Brown garden eel	Z	
x		*Heteroconger longissimus*	Brown garden eel	Z	
x- MNS		*Hippocampus UNK*	Pipefish	I	
x-MNS		*Holacanthus bermudensis*	Blue angelfish	I	
x-MNS		*Holocanthus Townsendi*	Townsend angelfish		
x-UNK		*Holacanthus UNK*	Angelfish	I	
x-MNS		*Hypleurochilus bermudensis*	Barred blenny	I	
x-UNK		*Hypoplectrus UNK*	Hamlet	I	
x-UNK		*Jenkinsia UNK*	Herring	Z	
x-MNS		*Labrisomus filamentosus*	Quillfin blenny	I	
x		*Lagodon rhomboides*	Pinfish	I	
x		*Lonchopisthus micrognathus*	Swordtail jawfish	Z	
x		*Lophogobius cyprinoides*	Crested goby	I	
x-NPR		*Lutjanus campechanus*	Red snapper	P	SP
x-UNK		*Lutjanus UNK*	Snapper	P	SP
x-MNS		*Malacoctenus boehlkei*	Diamond blenny	I	
x-MNS		*Malacoctenus gilli*	Dusky blenny	I	
x-MNS		*Malacoctenus triangulatus*	Saddled blenny	I	
x-MNS		*Malacoctenus UNK*	Scaly blenny	I	
x		*Manta birostris*	Giant manta	Z	
x-MNS		*Microgobius carri*	Seminole goby	Z	
x		*Microgobius signatus*	Microgobius signatus	Z	
x-UNK		*Microgobius UNK*	Goby UNK	H	
x-UNK		*Mullidae UNK*	Goatfishes	I	
x-UNK		*Muraenidae UNK*	Moray eel	P	SP

Assigned Attribute (1)	FL Assigned Attribute (2)	Species Name	Common Name	Guild (Caldow 2009)	Large (LP) or Small Piscivore (SP)
x-NPR		*Mycteroperca microlepis*	Gag	P	SP
x-NPR		*Mycteroperca phenax*	Scamp	P	SP
x-UNK		*Mycteroperca UNK*	Grouper UNK	P	SP
x-UNK		*Myrichthys UNK*	Snake eel	I	
x-MNS		*Nes longus*	Orangespotted goby	I	
x		*Nicholsina usta*	Emerald parrotfish	H	
x		*Ogcocephalus nasutus*	Shortnose batfish	I	
x-UNK		*Ophichthidae UNK*	Snake eel UNK	P	SP
x-UNK		*Opistognathus UNK*	Jawfish	Z	
X-MNS		*Oxyurichthys stigmalophius*	Spotfin goby	I	
x		*Pareques umbrosus*	Cubbyu	I	
x-MNS		*Platybelone argalus*	Keeltail needlefish	P	SP
x-UNK		*Pomacanthus UNK*	Angelfish	I	
x-NPR		*Ptereleotris calliura*	Blue dartfish		
x		*Ptereleotris helenae*	Hovering dartfish	Z	
x		*Remora remora*	Common remora	Z	
x		*Rypticus bistrispinus*	Freckled soapfish	P	SP
x		*Rypticus maculatus*	Whitespotted soapfish	P	SP
x		*Scartella cristata*	Molly miller	H	
x-UNK		*Scarus UNK*	Parrotfish	H	
x-UNK		*Scorpaena UNK*	Scorpionfish UNK	I	
x		*Scorpaenodes caribbaeus*	Reef scorpionfish		
x		*Serraniculus pumilio*	Pygmy sea bass	I	
x		*Serranus subligarius*	Belted sandfish	I	
x-UNK		*Serranus UNK*	Seabass UNK	P	SP
x-UNK		*Sparisoma UNK*	Parrotfish	H	
x		*Sphyraena borealis*	Northern sennet	P	SP
x		*Stephanolepis hispidus*	Planehead filefish	H	
x		*Stephanolepsis setifer*	Pygmy filefish	H	
x-UNK		*Stromateidae UNK*	Butterfish	P	SP
x-UNK		*Syacium UNK*	Sand flounder	I	
x-MNS		*Sygnathus dawsoni*	Pipefish	I	
x		*Synodus intermedius*	Sand diver	P	SP
x		*Synodus saurus*	Bluestriped lizardfish	P	SP
x-MNS		*Tigrigobius dilepis*	Orangesided goby	I	

Assigned Attribute (1)	FL Assigned Attribute (2)	Species Name	Common Name	Guild (Caldow 2009)	Large (LP) or Small Piscivore (SP)
x		*Trachinocephalus myops*	Snakefish	Z	
x-UNK		*Triglidae UNK*	Searobin Family UNK	I	
x		*Tylosurus crocodilus*	Houndfish	P	SP
x-NPR		*Urobatis jamaicensis*	Yellow stingray		
x		*Xyrichtys martinicensis*	Rosy razorfish	I	
x		*Xyrichtys novacula*	Pearly razorfish	I	
x-UNK		*Xyrichtys UNK*	Razorfish	I	

Appendix P – Fish Metrics Used in Developing BCG Rules

Metric	Description	Ecological Rationale
Total taxa - Species richness	# of fish species at the site	Reef fish communities on healthy coral reefs are characterized by high species richness and diversity (Ault and Johnson 1998), often correlated with habitat structural complexity and heterogeneity (MacArthur 1972; Risk 1972; Talbot and Goldman 1972; Luckhurst and Luckhurst 1978; Gladfelter et al. 1980; Carpenter et al. 1981; Hixon and Beets 1989; Shepherd et al. 1992; Grigg 1994; Galzin et al. 1994; Friedlander and Parrish 1998), and the proportion of live coral (Carpenter et al. 1981; Sano et al. 1984, 1987; Bell and Galzin 1984, 1988; Jones et al. 2004; Komyakova et al. 2013).
Biomass (species or station)	Total weight of all individuals	Biomass can refer to *species biomass*, which is the mass of one or more species, or to *station biomass*, which is the mass of all species observed at the station. High fish biomass, resulting from high density and large fish size, is typical in coral reef ecosystems in excellent condition (Russ 1985; Sandin et al. 2008; Dugan and Davis 1993). Biomass is calculated as the weight of all fish at a station using the power function: $W = a \times L^b$, where W is the weight (grams), L is the length (cm), and a and b are parameters estimated by linear regression of logarithmically transformed length-weight data. The parameters a and b are shown in the BCG Data Taxa Master spreadsheet, along with the weight-length conversion factor. Most of the length-weight relationships were determined from southern Florida specimens (Bohnsack and Harper 1988, with exceptions as noted from Bohnsack and Harper 1988, Bullock et al. 1992, Claro and Garcia-Arteaga 1994, and Letourneur et al. 1998). For the fish BCG, biomass was calculated for each species in a station, and for the entire station (all fish biomass combined).
Species Abundance	Total # individuals per species	The abundance of different species can provide insight into how the reef fish community functions (Nagelkerken et al. 2001). In the case of the BCG, changes in abundance can be used to infer changes in habitats and/or intensity of threats, such as fishing pressure (Alvarez-Filip et al. 2013). Caribbean reef-fish assemblages have been experiencing profound changes in community composition since 1980, probably largely due to habitat degradation; with . generalists replacing habitat-specialists over a 30-year period, indicative of anthropogenic disturbance (Alvarez-Filip et al. 2013).

Metric	Description	Ecological Rationale
Abundance of Fish by BCG Attribute	Total # individuals	The BCG Attributes respond to stressors in distinctly different ways, so they are predictive, quantitative measures along the full range of stress levels. "For example, highly sensitive taxa might disappear from a community in early, or low, levels of stress. Tolerant taxa might become more dominant as stress increases, not only because they might thrive, but also because there are fewer sensitive species and the proportion of tolerant taxa in the entire community increases. Intermediate tolerant taxa might not provide a significant signal under most conditions if they are present under a wide range of stress. However, the absence of this group of taxa in highly stressed conditions can help document highly disturbed conditions, and their reappearance may indicate initial response to management actions for restoration" (EPA 2016).
Family: Groupers	# of individuals	Groupers are recognized as sentinel or keystone piscivore taxa that, when present, indicate a complete trophic structure on the reef. Groupers are common and are expected to be observable on high quality reefs using the sampling methods employed for the FL/PR/USVI surveys. Other large predators might not be as common and might not always be observed. The BCG experts categorized groupers as large and small according to genera. Groupers are taxa in the recently re-organized Epinephelidae family (Ma and Craig 2018). Large groupers include all species in the *Epinephelus* and *Mycteroperca* genera (Rock hind, Red hind, Atlantic goliath grouper, Red grouper, Nassau grouper, Black grouper, Yellowmouth grouper, Gag, Scamp, Tiger grouper, and Yellowfin grouper). Other (smaller) groupers might be observed in areas that have been overfished for the large groupers. They include taxa in the *Cephalopholis* and *Dermatolepis* genera (Graysby, Coney, Atlantic creolefish, and Marbled grouper). Large, predatory groupers are present in healthy reef fish communities (Beets and Friedlander 1992, 1998; Beets 1997; Olsen and LaPlace 1979)
Family: Parrotfish	# of large-body parrotfish	Parrotfish are herbivores that trim algal turf around hard coral colonies. They might also eat the live coral tissue near algal mats. They are generally considered beneficial and indicators of intact reef systems. The Parrotfish metrics were calculated to include all taxa with Parrotfish in the common name. This included all species in the *Scarus* and *Sparisoma* genera as well as *Cryptotomus roseus* (Bluelip parrotfish) and *Nicholsina usta* (Emerald parrotfish). Large body parrotfish are common in reefs with good condition and are important in the control of macroalgae due to their large size (Randall 1963).

Metric	**Description**	**Ecological Rationale**
Family: Damselfish	% of total taxa	Damselfishes are highly territorial herbivores, aggressively excluding other herbivore groups such as surgeonfishes, tangs and parrotfishes from their feeding territories (Emery 1973; Robertson et al. 1976; Sammarco and Williams 1982. Many damselfishes cultivate algal gardens on coral heads (Irvine 1980; Lassuy 1980; Hixon and Brostoff 1983; Horn 1989), which can contribute to phase shifts in coral reef communities. Damselfish are expected to be on the reef in moderate numbers. If they are highly dominant in terms of numbers of individuals, then the sample is considered out of balance, indicating poor biological conditions. Damselfish were counted as all taxa in the Pomacentridae family. In the project dataset, this included 14 taxa in the following 4 genera: *Abudefduf, Chromis, Microspathodon,* and *Stegastes*.
Trophic Group: Piscivores (predators)	# of individuals	Coral reef ecosystems are shaped by apex predators and their presence indicates a relatively intact system. Loss of apex predators alters the patterns of predation and herbivory, leading to shifted benthic dynamics (Pauly et al. 1998; Pinnegar et al. 2000; Borer et al. 2005; Heithaus et al. 2007; Estes et al. 2011); top carnivores have specialized niches that when depleted can lead to a cascade of species extinctions (Pauly et al. 1998; Jennings and Polunin 1997; Christensen and Pauly 1997; Friedlander and DeMartini 2002; Steneck et al. 2004; Stallings 2008, 2009) and make them more vulnerable to natural and anthropogenic disturbances (Hughes 1994; Jackson et al. 2001; Hughes 1994; Gardner et al. 2003). Predators can exert a strong top-down control on the entire coral reef ecosystem and are importance in maintaining ecosystem function (Friedlander et al. 2013). Note: Red lionfish are predators but are not considered advantageous because they are invasive and might displace or prey upon native species. Therefore, lionfish are not included in metrics related to piscivores/predators.
Large-Bodied Fish (Large groupers, Large predators)	# of large-bodied groupers # of large-bodied piscivores	Coral reef ecosystems are shaped by apex predators and their presence indicates a relatively intact system. Loss of apex predators alters the patterns of predation and herbivory, leading to shifted benthic dynamics; top carnivores have specialized niches that when depleted can lead to a cascade of species extinctions and make them more vulnerable to natural and anthropogenic disturbances. Large predators are less common than small predators, perhaps because they are targets for fisheries or because they require a complete array of prey species. In better biological conditions, large predators are expected. In fair conditions, at least small predators are expected.

Metric	**Description**	**Ecological Rationale**
Sensitive Taxa (BCG Attributes I, II and III	# of taxa	A high percentage of sensitive species (Attributes I, II and III) indicates a system with minimal stress pressure. Moderate pollution can produce changes in taxa so that diversity remains similar to natural but species composition shifts (e.g., numbers of sensitive forms decrease while numbers of tolerant species increase (Odum 1985; Rapport and Whitford 1999; EPA 2016).
Rare, endemic, special species	# of taxa	Attribute I species are historically documented, long-lived, or regionally endemic taxa; They may be listed as Endangered or Threatened (E/T) or special concern species. Long-lived species are especially important as they provide evidence of multi-annual persistence of habitat condition or of minimal fishing pressure. For example, several shark species historically found on Caribbean coral reefs are now functionally extinct (Bonfil 1996; Ward-Paige et al. 2010).
Highly sensitive taxa (BCG Attribute II species)	# of taxa	Highly sensitive taxa typically occur in low numbers relative to total population density, but they might make up a large relative proportion of richness. In high quality sites, they might be ubiquitous in occurrence or might be restricted to certain micro-habitats. Their populations are maintained at a fairly constant level, with slower development and a longer life-span. They might have specialized food resource needs, feeding strategies, or life history requirements, and they are generally intolerant to significant alteration of the physical or chemical environment. They are often the first taxa lost from a community following moderate disturbance or pollution.

[1] α and β are coefficients obtained from FishBase (Froese and Pauly 2002) for calculating biomass (see Santavy et al. 2012). Biomass for species with no published length-weight relationships can be calculated using terms for the closest congener based on morphology.

Appendix Q – Recommendations for Future Research

Several issues that arose during discussions require further investigated. The issues are discussed below with possible approaches for resolution.

4. Recommendations from the full group (both benthic and fish experts)

1A. The Generalized Stressor Axis (GSA)

Anthropogenic activities can cause disturbances that exceed the range of natural variability, exerting pressure on the coral reef ecosystem by altering fundamental environmental processes, generating stressors that alter the state of the environment, and adversely impacting biotic condition (Niemi and McDonald 2004). Stress-response relationships are complex and not one-to-one. Stressors may affect more than one aspect of biological condition, and changes in biological condition may be the result of multiple stressors acting simultaneously. Many stressors co-occur in time and space. Coral reef organisms are increasingly being subjected to the cumulative impacts of multiple stressors. Stressors affect biological assemblages and ecosystem processes both directly and indirectly, including altering metabolic pathways, energy availability, and behavior of the organisms (Karr et al. 1986; Adams 1990; Poff et al. 1997). Stressors may affect more than one aspect of biological condition and a particular change in biological condition can also be the result of multiple stressors acting simultaneously.

Since multiple stressors are usually present, the x-axis represents their cumulative spatial/temporal co-occurrence in a generalized stressor axis (GSA), much as the y-axis generalizes biological condition (**Figure Q-1**). The BCG curve represents the *in-situ* response of the resident biotic community to the sum of stresses to which that community is exposed.

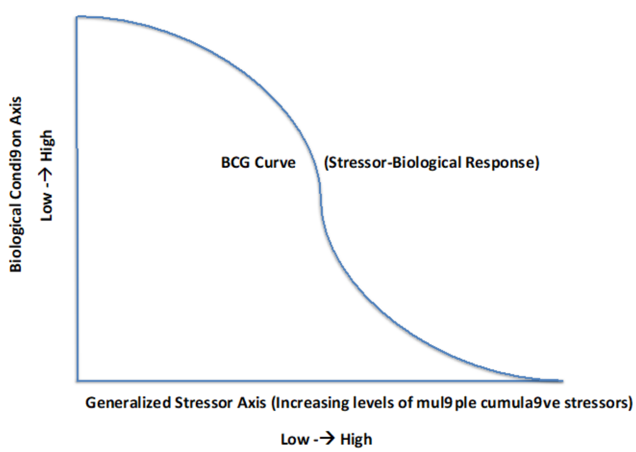


Figure Q1. The Biological Condition Gradient Conceptual Model. The Y-axis is the biological condition, the x-axis is the generalized stressor gradient, and the BCG curve show the response of the biota to increasing levels of stressors.

EPA and the coral reef experts discussed the concept of a generalized stressor axis (GSA) and focused on three stressors that should be considered for coral reefs: (1) land-based sources of pollution (sediment), (2) fishing pressure, and (3) global climate change-associated thermal anomalies.

Elevated Sea Surface Temperature (SST). Most coral reefs occur in tropical latitudes between 22 °S and 22 °N, experience relatively limited seasonal changes in water temperatures (4-5 °C) and average maximum temperatures of ~30 °C (Kleypas et al. 1999). Corals bleach in response to stress, including sudden changes to light, temperature, and salinity, the presence of toxins and microbial infections (Hoegh-Guldberg et al. 2011). The first small-scale coral bleaching episode was reported at the Great Barrier Reef in March 1929 (Yonge and Nichols 1931), when sea surface temperature (SST) had reached 35°C. However, it is only since 1979 that large-scale bleaching events that affect most, if not all, of the reef- building corals across entire reefs, regions, and countries have occurred as a result of warm water coral reefs being exposed to rising SSTs (Glynn 1979, 1988a, 1991; Goreau et al. 1992; Hoegh-Guldberg and Smith 1989; Glynn 1993, 2012; Hoegh-Guldberg 1999, 2011; Glynn et al. 2001; Hoegh-Guldberg et al. 2007, 2014; Baker et al. 2008; Eakin et al. 2010; Strong et al. 2011; Gattuso et al. 2014). Elevated SSTs are correlated with mass bleaching events (Goreau et al. 1992; Glynn 1988b, 1991; Hoegh-Guldberg 1999; McClanahan et al. 2007; Meissner et al. 2012). Sea surface temperatures have been rising as a result of anthropogenically induced global climate change.

Bleaching adversely impacts growth and reproduction of corals, and their vulnerability to a range of diseases (Harvell et al. 1999, 2007; Bruno and Selig, 2007; Baker et al., 2008). A reduction in reef-building corals also adversely impacts the fish species that live on the reef - fish species reliant on live coral cover for food and shelter (some 62% of reef fish species) decreased in abundance within 3 years of disturbance events that reduced coral cover by 10% or more (Wilson et al. 2006; Glynn 2012).

Sediment Threat (ST). Sedimentation from development along tropical shorelines and runoff from agricultural land use is widely considered to have adversely impacted coral reef ecosystems. Risk and Edinger (2011) documented the adverse impacts to stony corals from increased sediment stress including: decreases in coral growth rates (Bak 1978; Dodge and Brass 1984: Dodge and Vaisnys 1977; Cortes and Risk 1985; Tomascik and Sander 1985. Acevedo and Morelock 1988; Rogers 1990); partial or total mortality (Bak 1978, 1983; Bak and Steward-Van Es 1980; Brown et al. 1990; Nugues and Roberts 2003), changes in coral population structure (Cortes and Risk 1984, 1985; Acevedo and Morelock 1988); Rogers 1990; Maragos 1974); changes in coral morphology (Bak and Elgershuizen, 1976). Logan (1988); and reduced species richness and diversity (Cortes and Risk 1985; Acevedo and Morelock 1988; Rogers 1983; Dryer and Logan 1978; Obura et al. 2000; Sheppard et al. 2000; Gabrié et al. 2000; Hodgson and Dixon 1988; Chou 1997; Dikou and van Woesik 2006; Chansang et al. 1981).

Sedimentation has been documented to adversely impact fish communities, particularly through impaired feeding, poor water quality, and changes to benthic habitat (Rogers 1990; Bejarano-Rodrigues 2006; Bejarano and Appeldoorn 2013; Wenger et al. 2015; Neves et al. 2016; Brown et al. 2017). Reduced light intensity due to turbidity affects the visual cues that many fish species rely upon, changing social and mating behavior (Järvenpää and Lindström 2004), and affecting predator avoidance and foraging success (Leahy et al. 2011), resulting in reduced fish abundance and diversity (Amesbury 1981; Mallela et al. 2007) and modified trophic structures (Harmelin-Vivien 1992). Species richness of key functional groups has been shown to significantly decline as turbidity increases (Moustaka et al. 2018).

Fishing Pressure. Reef fish species have been subjected to intense fishing pressure (Munro 1983; Hughes 1994; Koslow et al. 1988; Williams and Polunin 2001; Jackson et al. 2001; Pandolfi et al. 2003; Newman et al. 2006; Ault et al. 2005). Large groupers and snappers, hogfishes, and the large parrotfishes are now rare, with a resultant loss of herbivory and predation (Pittman et al. 2010; Appeldoorn 2011; Ault et al. 2005, 2013). The reduction of these species has resulted in "trophic level dysfunction" (Steneck et al. 2004), with food chains now dominated by small fishes and invertebrates (Hay 1984, 1991; Knowlton et al. 1990; Appeldoorn and Meyers 1993; Jackson 1997). The reductions in the abundance and sizes of herbivores (e.g. , parrotfishes, surgeonfishes, and sea urchins) has resulted in some locations with increased abundance of macroalgae that compete with stony corals (Randal 1961; Lewis 1986; Lirman 2001; Hughes et al. 2007; Jackson et al. 2014).

The Puerto Rico reef fishery declined steadily beginning in the 1930s and then accelerated rapidly in the late 1950s with massive fishing pressure (Appeldoorn personal communication). In contrast, reduction in fishing pressure and resultant increases in fish populations has been shown in the Tortugas Ecological Reserve in Florida, including density, and abundance within management zones for a suite of exploited and non-target species (Ault et al. 2006, 2013).

EPA began research to develop a GSA, however, the GSA was not completed during the development of the BCG. A summary of GSA research completed thus far is included as **Appendix K**.

This is a priority project, not only for coral reefs, but for all coastal marine and estuarine ecosystems. Coastal marine and estuarine stressor gradients cannot be as clearly defined as those in streams. Streams have a distinct catchment and actual flow where the distance from a source to a given sampling site can be measured. Coastal marine and estuarine ecosystems are non-linear systems, and land-based stressors from multiple watersheds may impact a given reef as they become dispersed by wave action, wind and oceanic currents. Coastal and marine ecosystems are additionally stressed by fishing pressure and rising water temperatures. Refinements in stressor modeling are needed to inform a comprehensive stressor gradient for the BCG require data with appropriate scale to the reef communities of interest.

1B. Undisturbed Baseline Conditions

Healthy waterbodies exhibit biological integrity, representing a natural or undisturbed state (EPA 2002, 2011). This undisturbed state is known as reference condition for biological integrity (Stoddard et al. 2006). The concept of reference condition arose from the objective of the Clean Water Act Section 101: "to restore and maintain the chemical, physical and biological integrity of the nation's waters". Biological integrity is defined as "the community of organisms having a species composition, diversity and functional organization comparable to those of natural habitats within a region" (Karr 1991). Reference condition for biological integrity is the baseline for the BCG (Davies and Jackson 2006). Because the BCG is grounded in natural condition, it provides an anchoring point in time and can help us to avoid problems associated with "shifting baselines", particularly those associated with large-scale stressors such as changes in climatic conditions or intense fishing pressure (Pauly 1995; Knowlton and Jackson 2008). It also can help practitioners and the public recognize that current conditions do not necessarily represent natural conditions (Davies and Jackson 2006).

One challenge in developing the coral reef BCG was the difficulty in determining reference condition for biological integrity (BCG Level 1). Coral reef monitoring information is historically limited. By the 1950s fish populations were already decimated (Goreau 1959; Jackson 1997; Greenstein et al. 1998; Jackson and Sala 2001; Jackson et al. 2001; Pandolfi et al. 2003). Several major events have affected the benthic community including a white-band disease (WBD) epizootic event in the late 1970s and early 1980s that reduced the Acroporid corals by up to 95% throughout their range (Gladfelter 1982; Weil 2003, 2009; Weil and Rogers 2011); the catastrophic die-off of *Diadema antillarum* in 1983-1984, which reduced the population by ~90% (Bak et al. 1983; Lessios et al. 1984; Lessios 1988a and b, 2005); major bleaching events in 1990, 1998, 2005, and 2010 resulting in significant losses of cnidarian species (García-Saiset al. 2006, 2008; Wilkinson 2005; Aronson and Precht 2001a; Weil et al. 2002, 2009; Gardner et al. 2003; Jackson et al. 2014).

As a result of these events, there were no available reference stations in Puerto Rico or USVI. BCG Level 1 was not expected to occur in PR or USVI and was not described conceptually or with BCG model rules. Reference condition for biological integrity is most likely unobservable in the Caribbean reefs that have been degraded through years of overfishing, climate change, and land-based pollutant inputs. As described in the report introduction, current biological integrity in Caribbean coral reefs is generally degraded in relation to past conditions. Conditions observed in the 1950's through scuba diving and underwater photography might represent conditions that were minimally disturbed. However, those observations were not common, usually were not systematically recorded, or were not observable by members of the expert panel. Observations and recording that are familiar to most members of the expert panel are mostly from the late 20th and early 21st centuries. While the expert panel might not have direct familiarity with undisturbed or minimally disturbed Caribbean reefs, they are able to conceptualize an undisturbed reef based on historical descriptions, early publications on taxa distributions and reef characteristics, and the trajectory of disturbance over time and across the region.

Most of the consensus ratings for the sites in the benthic dataset were 3, 4, or 5. Level 2 samples were only recognized in calibration of the narrative model and Level 6 samples were uncommon. There were conceptual rules developed for Level 2 and quantitative rules calibrated for Levels 5 and 6. Validation ratings were at Levels 3 through 6, leaving the Level 2 rules un-validated. There was no attempt to outline benthic BCG model rules for Level 1 because this condition could not be confidently quantified. Level 1 conditions were conceptualized through review of historical records and by back-casting from current trends in reef degradation (Weil 2020, **Appendix L**). Weil describes considerable recent disturbances of both natural/climatic and anthropogenic origin. Historical and recent studies describe how historically dominant coral species decline, and weedy, opportunistic and more persistent species increase in abundance and cover over time due to Climate change, overexploitation, pollution and disease (Knowlton 2001; McClanahan et al. 2007; Green et al. 2008; Alvarez-Filip et al. 2011; García-Sais et al. 2017). This was documented in recent years in the Caribbean where live coral cover declined from more than 50% on average in the 1970's to just 10-15% by 2002 (Gardner et al. 2003, Jackson et al. 2014). The description of possible Level 1 conditions is informative regarding a biological baseline that is virtually impossible to observe in the Caribbean at the present time.

The fish consensus ratings were also mainly Levels 3 or 4 for both the calibration and validation sites. There were no ratings at Level 2, so while quantitative rules were developed, they were not calibrated or confirmed. There were no validation ratings at Levels 5 or 6, so those rules were not validated.

BCG Level	Fish Calibration Sites	Fish Validation Sites	Benthic Calibration Sites	Benthic Validation Sites
1	0	0	0	0
2	0	0	0	0
3	10	11	19	1
4	11	3	34	8
5	5	0	13	4
6	1	0	0	4

Calibrating the model with surveys from relatively unimpaired areas elsewhere in the Caribbean may be useful in further testing the reference condition attributes; however, differences in survey protocols may present a complication. Regional reference conditions are based on measurements from populations of least disturbed sites within a relatively homogeneous region using abiotic characteristics such as human population density and distribution, road density, and the proportion of mining, logging, agriculture, urbanization, grazing, or other land uses (e.g., Least Disturbed Condition (LDC) (Stoddard et al. 2006). Additionally, for coral reef ecosystems, current and historical fishing pressure is also a factor to consider. Two approaches are suggested for consideration as future research:

1. Conduct a new coral reef survey at a long-established marine reserve to establish minimally disturbed reference condition. It was suggested by the experts that Gardens of the Queen National Park, Cuba, would be an appropriate location to establish coral reef ecosystem minimally disturbed condition. Gardens of the Queen National Park, about 850 square miles of islands and reefs, is one of the most unspoiled environments in the Caribbean. A coral reef survey would be required, using methods comparable to the NCRMP methodology: every station would include a Line-point Intercept (LPI) Survey, coral demographic survey, topographic complexity survey, reef visual census (RVC) fish survey, and water quality survey.
2. Mine coral reef monitoring program data from the Atlantic and Gulf Rapid Reef Assessment (AGRRA) which has been collecting coral reef data throughout the Caribbean since 1997. Early in their program, AGRRA conducted baseline assessments of remote reefs in locations such as Cuba, the Bahamas, Panama and Los Roques National Park, Venezuela. AGRRA has collaborated with teams of scientific professionals and partners to collectively conduct over 3,000 surveys. The AGRRA methodology is very similar to the NCRMP and produces comparable data. AGRRA data is publicly available through their data portal.

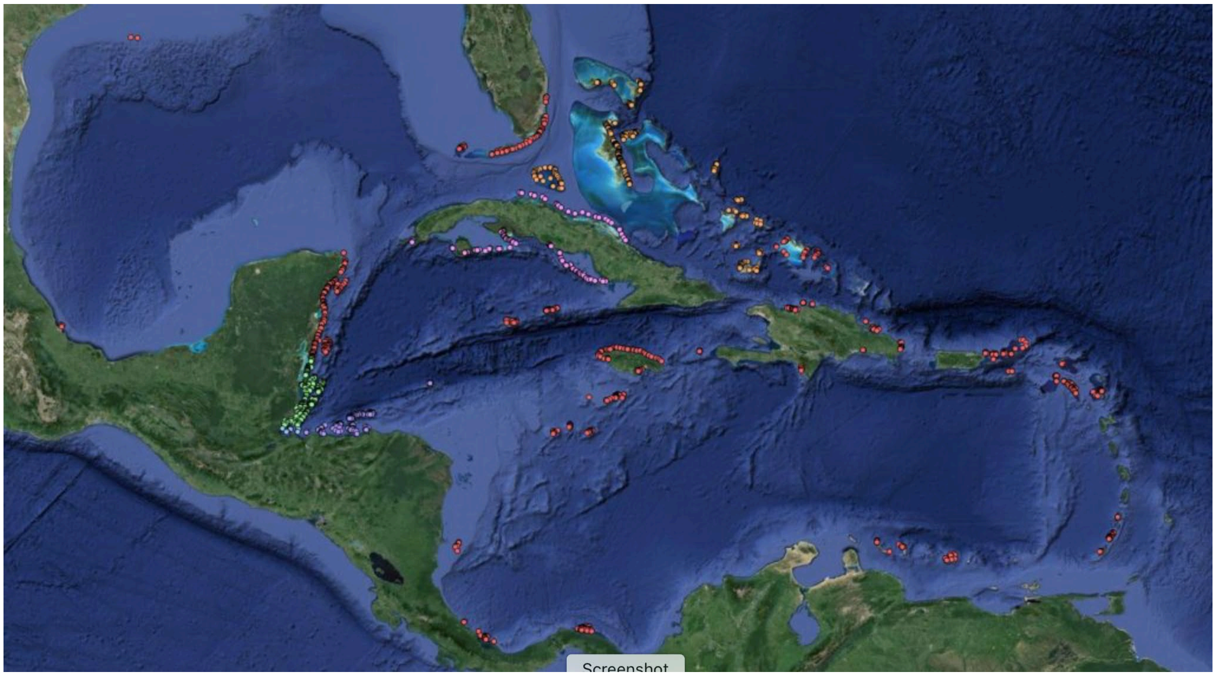


Figure Q2: Map of AGRRA Survey Locations in the Greater Caribbean. The Greater Caribbean extends from the Bahamas, Florida and Gulf of Mexico in the north through the Caribbean Sea to the south along the NE coast of South America; including the Greater and Lesser Antilles to the East and Central America to the west. Caribbean coral reefs have 65 stony coral species that provide homes to a diverse array of plants and animals, including nearly 700 reef fish species.

1C. Habitat Classification.

In designing a coral reef biocriteria program, it is important to be able to distinguish a signal of anthropogenic stress to the biological assemblages from noise caused by natural spatial and temporal variation (Jameson et al. 2001; EPA 2016). Establishment of reference condition is dependent upon a classification system that groups natural coral reef systems by physical and biological community characteristics to ensure that biotic responses are attributed to stressor intensity after accounting for differences in natural expectations (Jameson et al. 2001; Edinger and Risk 1999). The challenge is to determine the minimum number of classifications that represent the range of relevant biological variation in a region that can be used to detect and describe the biological effects of human activity in that location (Karr and Chu 1999; Jameson et al. 2001).

Coral reef environments have distinct horizontal and vertical zones created by differences in depth, wave and current energy, temperature, and light (Stoddart 1972; Zitello et al. 2009). A zone, as defined by Wells (1954) is “an area where local ecological differences are reflected in the species associated and signalized by one or more dominant species”. Because of this zonation, coral reefs cannot be considered homogeneous: sampling and corresponding analyses must take the zones into consideration. Important physical traits to consider while determining expected benthic species composition of a location include reef zones, geology, sea level change, sediment exposure, and decadal temperature anomalies (Stoddart 1972; Hubbard 1997; Hubbard et al. 2009; Costa et al. 2009; 2013; Zitello et al. 2009). The factors used for classifying reef types that affect biological expectations should include environmental variables that are not greatly influenced by human activity. For example, reef zones defined by depth and currents are not likely to change with human activity. Sediment exposure might be caused by natural sources of sediment or by excessive erosion from terrestrial human activities. If sediment from human activities, then sediment exposure would not be an appropriate classification variable.

Habitat classification is important when monitoring and assessing any biological assemblage, including fish communities. In coral reef ecosystems, there is a strong positive correlation of habitat complexity with fish species richness (Luckhurst and Luckhurst 1978; Carpenter et al. 1981; Roberts and Ormond 1987; McClanahan 1994; McCormick 1994; Green 1996; Friedlander and Parrish 1998; Sale 1991; Friedlander et al. 2003; Gratwicke and Speight 2005a, b; Kuffner et al. 2007; Pittman et al. 2007; Aguilar-Perera and Appeldoorn 2008; Walker et al. 2009; Smith et al. 2011).

To establish the foundation for the benthic BCG model, the benthic expert panel selected a habitat classification framework as the basis for rule development and to guide future monitoring. The panel's consensus was to limit the model to the *fore reef zone*; defined as the area along the seaward edge of the reef crest that slopes into deeper water on the barrier or fringing reef type (Costa et al. 2013). Features associated with a non-emergent reef crest but still having a seaward-facing slope that was significantly greater than the slope of the bank/shelf, were also designated as fore reef. The fore reefs were further divided into two zones; one was dominated by *Orbicella* species, and the other was colonized hard bottom with gorgonian plains (Williams et al. 2015). The former zone was used in this study. This approach should provide a template for application to other well-defined coral reef habitats (e.g., deep fore reef/escarpment with coral reef coverage) for future evaluations.

Based on the combined comments of the benthic and fish expert panels, a research project to develop a standard classification system and GIS dataset to describe and map coral reef ecosystems of Puerto Rico and USVI for use in biocriteria reporting is proposed. The project would begin by using the maps (Kendall et al. 2001) to identify the location of coral reefs and the habitat classification of those reefs. Lidar or another approach would be used on the reefs to improve reef classification. Finally, divers would conduct reconnaissance dives to ground-truth and refine the Lidar classifications and maps.

The refined reef classifications would be used in selecting representative transect locations when designing the coral reef monitoring program for BCG application. During reconnaissance, habitat strata can be identified from maps. If an assessment is then intended for application of the benthic BCG model, fore-reef or hardbottom habitat can be targeted for locating sites and confirmed on location at the surface and again underwater. If sites are selected in a probabilistic design, the general reef location can be completely randomized for all locations within the strata, but placement of the transect can be more purposeful; selecting specific transects at the location that are the intended habitat and representative of the broader location on the reef. This could allow avoidance of large sandy patches when the intention is to assess coral reef conditions.

To avoid unproductive sampling trips to locations that are determined to be inappropriate for assessment, there might be justification for establishing fixed transect sites that would be revisited annually or on another repeated schedule. Permanent transects would allow trend analysis in locations that are determined to represent an important reef type, location, or stressor condition. Comparisons over time in the same location with comparisons only in that location would avoid arguments of unrepresentative assessments due to habitat classification, transect location, depth, or other differences among sites. While permanent transects allow trend analysis within fixed stations, the sampling effort might displace one-time samples from multiple locations. The sampling program and purpose might have reason for only one or both types of sampling designs.

The proposed fine-scale mapping and assessment program can then be paired with the national and territorial scale NCRMP monitoring program to provide a nested, multi-scale assessment approach (Hawkins et al. 2000; Hughes and Peck 2003; NOAA 2014).

1D. Transferring the BCG to Other Jurisdictions

While the BCG model was developed using data from Puerto Rico, it is important to note that the BCG is a general framework that could potentially be applied to other coral reef ecosystems. To test the potential transferability of the Puerto Rico model to a different jurisdiction, the experts rated 14 stations collected in the Florida Keys and Dry Tortugas at depths shallower than 16 m, which were co-sampled by both the fish and benthic teams (RVC 2014-2016). The stations were selected by the RVC leads across a stressor gradient: water quality (low anthropogenic impact – Dry Tortugas, low-moderate impact – Florida Keys forereef, and high impact – Hawk's Channel); and fishing pressure based upon management zones (low – Dry Tortugas National Park, medium – Florida Keys, Marine Protected Areas, high – Florida Keys outside of Marine Protected Areas). BCG attributes were not revised, with one exception - species not observed in Florida were assigned an "x".

The quantitative Fish BCG model developed for Puerto Rico was 79% accurate in replicating the expert panel assessments within one-half BCG Level for the Florida Keys calibration. For mis-matched sites, the rule that was not met was the biomass rule. The experts felt that species attribute assignment might need to be revisited due to variations in fishing pressure at different jurisdictions. A full BCG calibration in Florida for both fish and benthic organisms is recommended. However, a less intense project would entail using the same 12 stations that were used for the fish BCG to test the Benthic BCG in Florida. Additionally, the BCG could be developed for Hawaii and the Pacific territories. This is a much larger project and would require multiple years and considerable effort to complete.

In general, the BCG conceptual framework is applicable to other coral reef ecosystems, as demonstrated by the proof-of-concept work done using sites from Florida Keys and Dry Tortugas. In order to use the BCG, other states and territories would need develop a numeric model scheme specific to their jurisdiction's coral reefs, using local monitoring data. The methods used to develop the BCG in Puerto Rico are likely applicable to other coral reef ecosystems (e.g., the process to elicit expert judgment). In some cases, the qualitative rules may be applicable (e.g., other Caribbean jurisdictions), but will require vetting by regional experts, using regional datasets to test and refine the rules. In all cases the quantitative rules are jurisdiction-specific.

5. Recommendations from the Fish Experts.

2A. Reconsidering Biomass: Age/Class Metrics for the Fish BCG

The data used for the Coral Reef Fish BCG documented composition, abundance, and size structure. This information was summarized into a set of indicators for each fish species - number of individuals of the species and biomass for that species. The BCG fish experts consistently expressed dissatisfaction with the fish biomass metrics and requested information about the size distribution (not just enumeration) of the fish observed.

Observations of juvenile and adult fish at a reef site might indicate that a full life cycle is supported at the site, inferring connectivity at the site for certain species. With observation of a single life stage, assessors are uncertain about the ability of the reef to support recruitment of juveniles or sustenance of adults.

During the field sampling, size was recorded in 5 cm intervals for all fish species, but association of juvenile and adult stages has not yet been completed for this data set. A listing of juvenile and adult size ranges for fish species might be available in the literature or might be created by the experts based on professional judgment. Enumeration of juvenile and adults (or size distribution) for future rating exercises would allow calculation of life-stage metrics for reef fish. Associating the life stages with size ranges might allow better discrimination of BCG Levels and connectivity. Various metrics can be generated from the size data, including:

- the total biomass for the station, in size bins
- station-wide ratio of biomass juveniles to adults
- species-specific ratio of biomass juveniles to adults
- species-specific mean length
- station-wide mean biomass
- station-wide median biomass
- species-specific mean biomass
- species-specific median biomass
- trophic group ratio of juveniles to adults (e.g., herbivores, piscivores, invertivores, etc.)
- trophic group median length
- trophic group mean length
- sample size class structure for all taxa

These metrics could then be tested to determine potential suitability for inclusion in the Fish BCG model; and could be subsequently developed into rules to improve the model's discriminatory capability.

Field Method for Measuring Structural Complexity.

Structural complexity is the physical three-dimensional structure of an ecosystem. For coral reef ecosystems, the structure is mainly provided by the physical shape and complexity of stony corals, octocorals, gorgonians, and sponges. Structural complexity can also be provided by geological features and underlying structures formed by dead organisms (Kleypas et al. 2001; Graham and Nash 2013). The importance of structural complexity for reef fish abundance, biomass and/or species richness has been well documented (Talbot 1965; Talbot and Goldman 1972; Risk 1972; Luckhurst and Luckhurst 1978; McClanahan 1994; McCormick 1994; Green 1996; Appeldoorn et al. 1997; Friedlander and Parrish 1998; Holbrook et al. 2002; Friedlander *et al*. 2003; Gratwicke and Speight 2005a, b; Kuffner et al. 2007; Purkis and Kohler 2008).

To estimate structural complexity, the EPA survey methodology measured linear rugosity using the chain-and-tape method, where the ratio between the length of a chain draped across the reef surface to the linear stretched length is calculated (Hobson 1972; Risk 1972; Talbot and Goldman 1972; McCormick 1994; Santavy et al. 2012). This ratio provided the rugosity index, accounting for important vertical dimensions.

The fish experts recommended revising the field method for measuring structural complexity because it does not fully reflect the three-dimensional availability of fish habitat. Several approaches have been developed that merit consideration. These methods should be evaluated to determine which would most appropriately give a measure of topographic complexity at the survey scale (i.e., site-scale as surveyed along a transect).

Methods to Evaluate

The NOAA NCRMP survey methodology is designed to capture basic information on three separate elements along a 25 x 4m transect: 1) slope (e.g., the minimum and maximum depth the transect); 2) vertical relief (e.g., the amplitude of substratum relief, recorded as the maximum vertical relief in the transect; and 3) surface area topography (e.g., an estimate of the relative proportion of different relief categories for the transect, using six different categories ranging from <0.2m to >2m.

Dustan et al. (2013) describe another approach, the Digital Reef Rugosity (DRR) technique, where a diver swims along a transect lone using a self-contained water level gauge as close as possible to the reef contour without bumping the bottom to characterize rugosity with non-invasive millimeter scale measurements of coral reef surface height at decimeter intervals along meter scale transects. The measurements require very little post-processing and can be easily imported into a spreadsheet for statistical analyses and modeling.

Storlazzi et al. (2016) describes a method that uses Structure for Motion (SfM) photogrammetry with geospatial software tools for characterizing 3D attributes of coral colonies. The method uses video that has been collected a part of the coral reef survey (e.g., Fisher et al. 2007) to produce high-resolution bathymetric models and rugosity of the seafloor. This method requires no additional field cost and lower hardware, software, and salary time than traditional remote sensing methods.

Walker et al. (2009) utilized a high-resolution Light Detection and Ranging (lidar) bathymetric survey to collect topographic measurements (i.e., surface rugosity, elevation, and volume) for the approximately 110 km^2 area in which all fish surveys were conducted. Lidar-measured topographic complexity may be a useful metric for predictive models of reef fish distribution.

2B. Ecosystem Connectivity - Seascape Ecology

Coral reefs are part of a tropical marine seascape that functionally links them with the adjacent shallow coastal habitats (e.g., tidal pools, saltmarshes, estuaries and bays, mangrove forests and seagrass meadows), pelagic habitats (e.g., shelf breaks) and unvegetated bottom (e.g., sand, hard bottom, and rock) (Meynecke et al. 2008; Mumby et al. 2008; Mumby and Hastings 2008; Hastings 2008; McCook et al. 2009; Miller and Lugo 2009; Schärer-Umpierre 2009; Sheaves 2009; Steneck et al. 2009; McMahon et al. 2012; Boström et al. 2011; Atkins et al. 2015; Pittman 2017; Lord et al. 2020).

Many reef fish respond to this spatial mosaic by showing pronounced associations with specific habitat types (Dahlgren and Eggleston 2000; Sale 1991; Cerveny 2006). Some reef organisms have life histories that depend on specific juvenile habitats that differ from those used by adults (Beck et al. 2001; Christensen et al. 2003; Aguilar-Perera 2004; Cerveny 2006; Aguilar-Perera and Appeldoorn 2007, 2008; McField and Kramer 2007; Cerveny et al. 2011; Atkins et al. 2015). For example, many juvenile fish prefer shallow water habitats such as mangroves and seagrasses, whereas the adult forms are found in adjacent coral reefs (Gratwicke and Speight 2005; Adams et al. 2006; Dahlgren et al. 2006). Rainbow parrotfish, grunts, barracudas and several snapper species depend on mangrove forests and seagrass beds for nursery habitat (Dorenbosch et al. 2006, 2007; Mumby et al. 2004; Machemer et al. 2012). Coral reefs provide essential habitat for many species of adult fish (Jones et al. 2004; Feary et al. 2007; Grober-Dunsmore et al. 2007) Spawning aggregation zones and currents (larval transport are essential characteristics for reproduction (Mumby and Steneck 2008; Schärer et al. 2010).

The tropical marine mosaic also supports "charismatic megafauna" such as large animal species with widespread popular appeal (*e.g.,* manatees and dugongs, sea turtles, rays, sharks and dolphins) (Heithaus 2007; Principe et al. 2012). Some of these species (*e.g.,* manatees and sea turtles) use a variety of habitats during different life stages (Lefebvre et al. 1999; McField and Kramer 2007; LaCommere et al. 2008).

Ecosystem connectivity (Attribute X) is therefore an important attribute to include in a coral reef conceptual model. Attribute X has typically been defined as access or linkage (in space/time) to materials, locations, and conditions required for maintenance of interacting populations of aquatic life; the opposite of fragmentation; necessary for metapopulation maintenance and natural flows of energy and nutrients across ecosystem boundaries. Possible examples: spatial proximity of coral reefs with mangroves, sea grass beds, and lagoons; flow of potential recruits from upstream and upcurrent sources (larval dispersal).

Three types of future research were recommended by the fish experts: 1) high-resolution reef bottom topography (LIDAR or other) and habitat maps to allow for better estimation of connectivity, 2) application of landscape ecology methods to coastal and coral reef ecosystems to identify metrics that can be used to quantify BCG Attribute X – Ecosystem Connectivity and 3) development of improved information on species and functional traits for Caribbean fish.

Ecosystem connectivity is a critical ecosystem attribute:

- Reproduction (spawning aggregation zones, larval dispersal);
- Critical foraging areas, nurseries and refugia;
- Physical and chemical buffering;
- Energy and material flows;
- Migratory corridors for transient species.

High Resolution Bottom Topography. One recommendation was that high-resolution reef bottom topography (LIDAR or other) and habitat maps are expected to allow for better estimation of connectivity (Prada et al. 2008; Lirman et al. 2010; Gintert et al. 2012). With high-resolution topography and habitat maps, features related to connectivity could be recognizable and quantifiable. High-resolution topography would also indicate elements of rugosity as well as potential for ontogenetic connectivity of fish species, allowing characterization of broad-scale relief and a possible basis for classification of reefs. NOAA, USGS, or ACOE might have/provide/generate the high-resolution data. This is considered a high priority and would require coordination among multiple agencies.

Application of Landscape Ecology Methods (Seascape Ecology). Landscape Ecology studies the spatial distribution of organisms, patterns and processes (Dramstad et al. 1996; Farina and Napoletano 2010), by focusing on three characteristics of the landscape (Forman and Godron 1986; Turner and Garner 1991; Forman 1995a, b; Turner et al. 2001): structure, function and change. Aspects of landscape ecology that are applicable to the seascape include patch dynamics, scaling, connectivity, fragmentation, corridors (Wiens et al, 1985; Urban et al. 1987; Forman and Godron 1986; Wiens and Milne 1989; Saunders et al. 1991; Wiens 1992; Wiens 1999, Wiens and Moss 2005; Pittman et al. 2011). In a facilitated discussion, the fish experts agreed that coastal and marine ecosystems are arrayed in space in response to gradients of topography, depth, water temperature, salinity, energy (wave regime, tide. etc.), rugosity and substrate type. Research has begun to adapt the biotope mosaic approach developed for estuaries (Cicchetti and Greening 2011; Fulford et al. 2011; Shumchenia et al. 2016) to the tropical marine seascape. A biotope is an area that is relatively uniform in physical structure and that can be identified by a dominant biota (Davies et al. 2004; Connor et al. 1997; Pittman et al. 2007a, b; Costello 2009; FGDC 2012;). The research will develop metrics of change for coastal and marine biotopes.

Development of improved information on species and functional traits. Important species traits might show patterns might influence their potential role as indicators in the BCG model. Reef fish data can be associated with the NOAA benthic habitat maps to help determine the expected assemblages in different habitats throughout a mapped space (Pittman et al. 2007a, b). For example, the main factors used to determine reef fish assemblages in biogeographic regions on the Southeast Florida reef tract were reef vs. hardbottom substrates, depth, relief, and geographic space (Fisco 2016). Important species traits might show patterns only found at inshore or only at offshore survey sites, exhibiting a distribution restricted by water depth, or geographically widespread across depth, which might influence their potential role as indicators in the BCG model. For example, the absence of a fish species from a nearshore site may not be indicative of the condition of the coral reef ecosystem if that species' range does not occur in nearshore reefs. Similarly, the frequent occurrence of a species in waters known to be impaired due to the influx of land-based pollutants may mean the species is more pollution-tolerant than a species found only in waters that do not contain influxes of land-based pollutants, assuming benthic variables are similar in both locations. The combination of the depth distribution, distance to shore, and the frequency of occurrence provide an indication of relative abundance for each fish species and a simplified geographical habitat width for each species. Improved information on species and functional traits for Caribbean fish could aid in improving and interpreting results when applying the BCG fish model to other Caribbean locations. Development of a matrix for reef fish species traits, similar to the matrix for benthic species Weil (2019; Appendix R) is recommended.

2C. Metadata for Caribbean Fish Species

During development of the BCG, Dr. Ernesto Weil was contracted to develop detailed information about Caribbean coral species (Weil et al. 2019; Appendix R). However, a similar effort was not undertaken for fish species. Detailed information is needed about the life history, biological, ecological and geographical characteristics of Caribbean fish species for future versions of the Fish BCG model.

Life History Traits

Longevity.

In coral reef ecosystems, large-bodied, slow-growing, late-maturing fishes (K-strategists) are generally more sensitive to exploitation than faster-growing, shorter-lived species (r-strategists) (Beverton and Holt 1957; Man et al. 1995; Jennings et al. 1998; Coleman et al. 2000; Goodwin et al. 2006; Ault et al. 1998, 2008). Consideration of K/r strategies informs coral reef fish population responses to environmental stress, which is largely determined by life-history traits with K-strategists being more susceptible to fishing pressure than r-strategists (Musick et al. 2000; Ault et al. 2005, 2008, 2014). The BCG Attribute definitions (Davies and Jackson 2006) include considerations of these life history traits: Attributes I and II include long-lived, late maturing, low fecundity species; while Attributes IV and V include early colonizers with rapid turn-over times and "boom/bust" population characteristics. However, species-specific life history data was not included in this BCG evaluation and was therefore not considered in the assignment of species to coral reef BCG attributes.

Habitat requirements (larvae, juvenile, adult).

Many coral reef fishes migrate into different habitats throughout their life stages - Ontogenetic migrations (i.e. progressive displacement of a given fish life stage from a given habitat to another). Identifying essential habitats and preserving functional linkages among these habitats is an important component of ecosystem integrity. Numerous studies have documented individual Caribbean species' habitat requirements by life-stage (Dennis 1992; Eggleston 1995; Rooker

1995; Appeldoorn et al. 1997, 2003; Lindeman 1997; Lindeman and Snyder 1999; Nagelkerken et al. 2000; Recksiek et al. 2001; Cocheret de la Moriniere et al. 2002; Christensen et al. 2003; Halpern 2004; Mumby et al. 2004; Dorenbosch et al. 2004, 2006; Lindeman and De Maria 2005; Aguilar-Perera et al. 2006; Gratwicke et al. 2006; Verweij et al. 2006; Aguilar-Perera and Appeldoorn 2007, 2008; Jones et al. 2010; Schärer-Umpierre 2008). The body of scientific knowledge on ontogenetic migration should be organized by individual species and life stage to better inform the BCG Fish Model.

Depth Preference.

While the composition and ecology of reef fish communities have been well characterized for the upper 30 meters, coral ecosystems can extend to depths of 100 m or more, with large gradients occurring in key physical parameters that are expected to have a significant impact on overall fish diversity and community composition. Recent studies of mesophotic reefs have shown that many shallow reef fish are also found in deeper waters (Colin 1974, 1976; Brokovich et al. 2010; García-Sais2010; Kahng et al. 2010; Bejarano et al. 2014), while others are only observed at shallow depths. Large commercially important species threatened by overfishing can also be found in mesophotic reefs (García-Sais et al. 2004; Feitoza et al. 2005; Bejarano et al. 2014; Laverick et al. 2016). Documentation of this information by individual species could inform additional BCG rules.

Reproductive strategies (spawning aggregations).

Many Caribbean coral reef fish species form large group aggregations to reproduce (Smith 1972; Munro et al. 1973; Johannes 1978; Olsen et al. 1978; Colin 1974; Carter and Perrine 1994; Sadovy et al. 1994a, b; Aguilar-Perera and Aguilar-Davilá 1996; Koenig et al. 1996; Domeier and Colin 1997; Sadovy and Ecklund 1999; Lindeman et al. 2000; García-Cagide et al. 2001; Sala et al. 2001; Claro and Lindeman 2003; Claydon 2004; Whaylen et al. 2004; Burton et al. 2005; Graham and Castellanos 2005; Heyman and Kjerfve 2008). There are two types of spawning aggregations ("resident" and "transient"), defined by using three criteria; the frequency of aggregations, the longevity of aggregations, and the distance traveled by fish to the aggregation. Resident aggregations are common to most rabbitfish, wrasses and angelfish. In resident aggregation, spawning is brief (often 1-2 hours), occurs frequently (often daily) and involves migration over short distances to the spawning site. Transient aggregations are used by most groupers, snappers, and jacks. When transient spawning aggregation sites are known and fished during the aggregation, then that species' population may be depleted due to unsuccessful reproduction. There is considerable literature available on spawning aggregations throughout the Caribbean that should be captured for use with the BCG Fish Model.

Shoaling and Schooling Behavior.

Many fish species stay together for social reasons (shoaling) and may consist of different species that hang out together. If the group is swimming in the same direction in a coordinated manner, they are schooling. Schooling provides benefits such as defense against predators (through better predator detection and by diluting the chance of individual capture), enhanced foraging success, and higher reproductive success. Schooling behavior is an attribute that should be included in the metadata. We recommend using the three categories were used in Claudet et al. 2010: 1) non-schooling (fish that are nearly always solitary), 2) facultative schooler (fish that can be seen in school aggregations), and 3) obligate schooler (fish that are always in schools).

Diet Specialization.

The feeding guilds for the Caribbean reef fish have been included in the Fish BCG assessment. However, fish feeding preferences may be either specialized or generalized. Generalists may forage on a variety of food items, while specialists are limited in their diet. Dietary specialization may increase a species' vulnerability to resource depletion.

Fishes that feed from live corals (corallivores) are a component of healthy coral reef ecosystems, demonstrating distinct prey preferences and generally consuming corals from the genera Acropora, Pocillopora and Porites (Cole et al. 2008). There are two categories of corallivores: obligate (defined as having a diet which is at least 80% coral) and facultative (defined as organisms that regularly consume coral without it comprising a large percentage of their diet) (Cole et al. 2008). Because obligate corallivores are dependent upon live coral for their diet, when there is increasing coral mortality, obligate corallivores decline proportionately (Pratchett et al. 2006). Identifying the corallivore species and assigning them to one of the two categories may provide information that could be incorporated into a future BCG rule.

6. Recommendations from the Benthic Experts.

3A. Photos and Videos at Survey Sites

During the sample review and BCG calibration process, the experts expressed that the data sheets alone were difficult to interpret without photographs. In some of the reviewed samples, the data sheets suggested that the site was either a highly degraded reef or a location that was not expected to naturally support a reef. Photos would help in confirming that the site is potential reef habitat.

Additional interpretive data could be gleaned from photographs, especially during expert reviews. The experts suggested that photographs and/or videos should be routinely and systematically taken at all sites, in the direction of the four compass points and along the sampled transects. Photos would allow interpretation for reconciling discrepancies perceived in the data, which could be used to refine BCG ratings or to confirm the outcome of BCG model application. If the photos and videos were to be used for quantitative rules in future BCG models, substantial post-processing would be required to translate the images into quantitative measures.

The expert recommendation is that the survey methodology adopted for Puerto Rico and USVI include a diver who makes a videographic record along the transects and takes photos of interesting and unusual features at each survey site. The diver will swim at a uniform speed, pointing the camera down and keeping the lens approximately 0.4 m above the substrate at all times. A guide wand or dropper weight attached to the camera housing should be used to help the diver maintain the camera a constant distance above the reef (Smith et al. 2015).

3B. LPI Surveys

Substrate categories in the LPI surveys should be refined, especially for the designation of "bare substrate". The experts were uncertain whether this was an indication of a hard surface devoid of life (not even algal turf) or it was always sand. If sand, the sand could be further characterized as clean and coarse or fine sediment (indicative of terrigenous sedimentation). Sand might occur in the troughs of a spur and groove system without indicating unproductive or degraded reef habitat. Because sand might not be displacing potential coral microsites, the experts suggested that coral cover could be calculated as a percentage of non-sand substrate. Recommendations for future surveys are to designate hard surface devoid of life, clean and coarse sand, or fine sediment.

The experts noted some differences in apparent reef characteristics between DEMO and LPI methods at the same site. The methods represent different levels of effort and measure different aspects of the benthic assemblage. On average, the LPI method yields higher coral cover values than the demographic method (Tetra Tech 2020). After assessing several samples and comparing to some photographs, the experts were in general agreement that a single 10m LPI transect was not enough to characterize a reef condition. They suggested a longer transect or more transects at the same site. Nadon and Stirling (2006) demonstrated that sampling 100 points on a 20 m chain transect using 5–10 randomly positioned replicates is a low cost, highly accurate, and precise method for estimating either low or high coral cover. The BCG benthic experts recommended using 4-5 10m transects.

Appendix R – Metadata for Caribbean Coral Species

Report submitted from: Dr. Ernesto Weil
Dept. of Marine Sciences
University of Puerto Rico

Technical Report completed under USEPA Contract EP-C14-022

The following tables present up-to-date information on life history, biological, ecological and geographical characteristics for all scleractinian coral species recognized in the wider Caribbean. The information was distilled by reviewing most of the available references, discussions with colleagues, and from my personal experience of diving and conducting research in the region for over 40 years. This is still an on-going work because we are still missing critical information (reproduction, distribution, life history, tolerance limits, threat susceptibilities, etc.) for many taxa from around the region. Hopefully, it will be completed over time, maybe by future generations, when this information finally becomes available. Even the alpha-taxonomy of at least 18 "ectomorphs" (20% of species listed) of which, 12 could end up being separated as true species) is still un-resolved.

The color codes in the table define important information about the particular species in relation to its threatened or endangered status according to the IUCN Red List, taxonomic status (if it is fully resolved and accepted, still unresolved, or if it is an invalid name), if it is an exotic, invasive species, an hydrocoral, and whether the species has a wide depth distribution, including to the mesophotic habitats below 40 m.

The first tables provide information on the current taxonomic status; Family, Sub-family, genus, the current and former (synonyms) species names used, the common names in English and Spanish, and the commonly used species acronym for all shallow water and upper-mesophotic (0-50m), mostly zooxanthellated coral and hydrocoral species in the wider Caribbean The only non-zooxanthellated genus included is the conspicuous and common *Tubastraea* (Dendrophylliidae), because of its abundance, accretion and wide geographic distribution, and the identification of the recent exotic-invasive *T. micrantus,* that is rapidly spreading. Shallow, non-zooxanthellated species in otherwise zooxanthellated genera are also included (i.e. *Madracis pharensis*). Small, cryptic, non-zooxanthellated species in the family Caryophyllidae are not included. Then, the known depth range which can vary across localities and regions.

Other tables include information (with categorization and/or rankings) for the most important life history and biological/ecological traits (reproduction, growth, mean size, common colony morphology, and finally the assessed susceptibility to three common threats (sedimentation, disease, and bleaching), that ultimately define the species survivorship, fitness and potential resilience. BCG attribute levels that are equivalent to the rankings (* to **** = low to high) used are presented for bleaching, diseases and sedimentation susceptibility. Finally, complementary information about the traits, local and geographic distribution, etc. is presented for the different species of scleractinian corals and hydrocorals. The table goes beyond the requested information for the BCG project but, I though this information would be useful in helping to put into context the traits that characterize the potential reef-building, survivorship, and resilience of the different taxa for this and future coral reefs EPA program that will likely assess the conditions and characterize the resistance/resilience and potential recovery of coral reef communities to the ongoing and future threats around the Caribbean.

Additional tables present up-to-date information of the number of common diseases affecting the different species of corals in the Caribbean, and the assessed/estimated susceptibility of each species to each one of those reported diseases. Because environmental stressors, host immune responses and pathogen (s) virulence can vary over time, the particular susceptibility ranking for each case is not fixed over time, or for any particular locality, and could change accordingly. Furthermore, surviving individuals to disease outbreaks in particular species and localities are assumed to be resistant to that particular disease, and their genetic combinations are expected to be passed on to future generations, potentially reducing the susceptibility to that particular disease, and maybe others. Similarly, pathogen's virulence can increase (mutation) affecting otherwise resistant or different hosts. These "negative" dynamics might not happen if environmental stressors are significantly reduced.

Bleaching susceptibility and signs are also variable and could change over time in the same coral species. They depend on the intensity and duration of thermal anomalies, other local environmental factors, the symbiont composition (resistant strains??), densities and intra- and inter-colony distribution, depth, light conditions, etc. that could be very significantly spatially and over time.

Relevant information and ranking criteria

Corals are **modular**, sessile invertebrates with a long evolutionary history (>400 MY) and complicated life histories and life cycles (Jackson and Hughes 1985). Modular, colonial organisms are unusual because the "organism-colony" is comprised of many, genetically identical, replicated, interdependent modules (polyps, zooids, etc.), each with its own birth and death rates, complicating analyses of life-history patterns and population dynamics (Baird et al. 2009). Colonies are in reality communities of many different organisms (cnidarian polyp, bacteria, algae, fungi, other protists, etc.,) living together in mutualistic and/or symbiotic relationships, and they are called **holobionts**. These evolutionary advantageous relationships could turn detrimental to the main "host" if conditions change and become stressful for one or several of the members of the community. Scleractinian reef-building corals are foundation species because they built the structural and energetic base of coral reefs, providing the complex three-dimensional primary framework that becomes essential fish habitat and habitat for thousands of other invertebrate species (Harrison and Booth 2007). Modularity is the primary cause of this.

Modularity provides several biological/ecological adaptive, emerging properties including; high genetic variability, survivorship and fitness. Modular organisms are potentially "immortal" since senescence only applies to the individual polyps, and polyps are continually (asexual reproduction) producing new polyps, so as the colony growths there is continuous "rejuvenation" provide by the new small modules (polyps) colony. Polyp size is limited by the capacity to move nutrients and energy within and determined by the surface/volume ratio relationship that limits maximum size in non-modular organisms. But there is no limit to how many polyps can be added to the colony and therefore, modular organisms potentially have no limits to how big they can get. Furthermore, the bigger the better, more polyps will increase feeding and photosynthesis area, competitive ability, survivorship, and ultimately, fecundity. Size is therefore, usually regulated by external stressors, diseases, predation, competition and other causes of partial mortality. Colonies can suffer 99% mortality but, if a couple of polyps survive, they start producing new polyps and eventually, the colony (genet) grows back and starts reproducing sexually again. Some coral colonies in modern coral reefs may have genotypes that are thousands of years old, carrying the information that allowed those colonies to survive environmental and biological disturbances over time. This genetic information keeps being passed on to new generations either by cross-breeding with much younger genotypes (across-generations), or with other, old genotypes. In either case, genetic variability continues to increase.

The total number of extant scleractinian "species" is not known, so estimating global coral species richness is complicated by a number of issues (Harrison 2011). High morphological variability within species is an issue for the still ongoing, imperfect (incomplete) taxonomic resolution of many taxa, and cryptic and/or sibling species. Limited exploration of deeper mesophotic coral communities, deep-sea environments, as well as some shallow tropical reef regions (far away and isolated reefs where new species are likely to be found, and furthermore, the discovery of hybridization among some morphologically different corals (morphospecies) are challenges for some corals still preventing the complete taxonomic resolution for the group (e.g., Oliver et al. 1992; Willis et al., 1997; Szmant et al. 1997; van Oppen et al. 2002; Vollmer and Palumbi 2002). The application of the traditional biological species concept based on reproductive isolation between different species has not been tested for all species. Assuming that the current primarily morphologically based taxonomy provides an appropriate indication of global coral species richness, there are at least 900 extant zooxanthellated scleractinian species (Wallace 1999; Veron 2000). Of these, 827 zooxanthellate hermatypic coral species have been assessed for their conservation status (Carpenter et al. 2008). In addition, there are at least 706 non-zooxanthellate scleractinians known, including 187 colonial and 519 solitary coral species mostly distributed between 200–1,000 m (Cairns 2007).

Paradoxically, the Caribbean has the older scleractinian genera, yet it shows a significantly depauperated coral diversity, with significant lower genera and species compared to the Indo-

Pacific. There are more or less 70 recognized zooxanthellated, mostly reef-building coral species, with still 12-18 "ecomorphs" (=20% of the total number of listed species) that need taxonomic verification. Over 150 non-zooxanthelated species have been identified (Cairns 2007).

Life History Traits

Life-history strategies in corals are complex and difficult to characterize because of modularity. Life history describe consistent, and context-independent characteristics of organisms. The classic two-strategy life-history framework of r–K models (Pianka 1970), is considered oversimplified, and/or mostly referring the "extremes " since many species usually show intermediate traits along the r-K continuum of 'fast' (r) to 'slow' (K) life histories (Stearns 1977). Three-strategy frameworks resolve some difficulties of r–K selection by adding a third 'beyond K' group of stress-adapted species that can persist in unfavorable habitats (i.e., via adversity selection, Greenslade 1983). For example, Grime's C–S–R triangle describes three life-history strategies in plants (modular organism), in which species are hypothesized to evolve strategies that promote competitive (C), stress-tolerant (S) or ruderal (R) life histories (Grime 1977; Grime and Pierce 2012). Trait-based approaches can provide general and predictable rules for community ecology, as well as a more mechanistic understanding of community assembly and disassembly, habitat filtering and species coexistence, particularly in the context of global climate change and overall community biodiversity loss (McGill et al. 2006). Species traits also provide important information about life-history strategies, which can broadly define how organisms interact with one another and their environment (Darling et al. 2012). These authors evaluated if life-history strategies can be directly inferred from species biological traits.

A few studies have considered how some coral traits may relate to life-history strategies. For example, small corals with brooding reproduction, fast growth rates and high population turnover are expected to be **'weedy'** (Knowlton 2001), while large, slow-growing colonies of massive corals are expected to be "**more tolerant"** to chronically stressful or variable environments (Jackson and Hughes 1985; Soong 1993; Rachello-Dolmen and Cleary 2007). Similarly, variation in colony morphology and reproductive mode are thought to suggest three primary life histories (competitors, stress-tolerant and ruderals (Edinger and Risk 2000; Murdoch 2007). Observations of increasing abundances of 'weedy' species (Green et al. 2008) and the persistence of massive species on disturbed Caribbean (Alvarez-Filip et al. 2011) and Indo-Pacific reefs (McClanahan et al. 2007; Rachello-Dolmen and Cleary 2007), suggest that life-history traits can predict which corals are 'winners' or 'losers' in the face of environmental change (Loya et al. 2001; van Woesik et al. 2012) which is an important consideration in many different projects. For example, branching and plating acroporid corals are dominant species that are very sensitive to stress and disturbance (i.e., 'losers'), while massive species and 'weedy' species are more likely to be 'winners' and persist in unfavorable and/or frequently disturbed environments (Loya et al. 2001; McClanahan et al. 2007). However, the underlying species characteristics that may predict these responses are difficult to evaluate without a comprehensive understanding of coral biological traits and associated life-history strategies.

Darling et al (2012) compiled a global database of species traits for reef-building corals and classified taxa into life-history strategies that can be used to evaluate ongoing community shifts on coral reefs. They used eleven species traits for which there is information in the literature: *colony growth form, solitary colony formation, reproductive mode and fecundity, maximum colony size, corallite diameter, depth range, generation time, growth rate, skeletal density and symbiotic zooxanthellae (Symbiodinium) associations,* and focused on traits that were expected to affect coral population dynamics, and for which quantitative data were available at a global scale. Still, it is not easy to rank all species since some have common traits across the different categories.

The Darling et al (2012) system aided by other literature was used to rank the "life history traits" for the different species in the table. Four categories were used: (1) **Weedy Species (W**)= Small branching and sub-massive colonies of mostly brooding spp. Small corallites, low fecundity but high survivorship and high variability in LH traits; (2) **Competitors (C)=** Large, branching, plating, and fast growing in shallow habitats. Broadcasters. High mortalities and susceptible to bleaching and fragmentation; (3) **Stress Tolerant (S):** Slow growing, dome-shaped, massive, sub-massive, and platy growth forms, Broadcaster with high fecundity and low survivorship, and (4) **Generalist (G)**= mixed C, S, and W strategies. Massive, sub-massive dome shapes, crustose or plates, slow growth, and brooders or broadcasters.

Reproduction

Modularity can potentially lead to a diverse array of sexual systems (Weiblen et al. 2000). However, unlike flowering plants (Barrett 1998), and some unitary/individual animals, there are essentially only two sexual systems in scleractinians. Colonies are either predominately out-crossing, **simultaneous hermaphrodites**, with each polyp producing both male and female gametes, or colonies have polyps that produce only one kind of gamete, one sex throughout their life (**gonochoric or dioecious**). Of the more than 1,500 recognized coral species, aspects of sexual reproduction have now been recorded in at least 444 species, the vast majority being shallow-water zooxanthellate and hermaphroditic species (Harrison 2011). Either of these two sexual patterns can show two different developmental modes; (1) those that liberate their gametes into the water column for external fertilization and embryogenesis (**broadcast spawners),** and (2) those that liberate well developed larvae into the water column after internal fertilization and embryogenesis (**brooders or planulators**) (Baird et al. 2009, Richmond and Hunter 1990, Harrison 2011).

Several taxa however show "mixed sexual patterns", with both gonochoric and hermaphrodite polyps, and/or "mixed developmental modes", with spawning and brooding polyps (Chornesky and Peters 1987; Soong 1991; Harrison 2011). Some of these findings however might have resulted from incomplete, or biased experimental designs of the research. Over the last 30 years, research on coral reproduction has advanced substantially, expanding into many reef regions that were not previously well studied, including equatorial and tropical regions of high coral biodiversity (Richmond 1997; Guest et al. 2005; Harrison and Booth 2007; Baird et al. 2009a). This has resulted in substantial new information and verifications and has almost doubled the number of coral species for which sexual reproductive data is now available for at least 444 species (Harrison 2011). The current global data generally confirm, correct and/or extend many of the trends and patterns highlighted in earlier studies, nevertheless some recent advances in our understanding of coral sexual reproduction summarized in Harrison (2011), left it clear that reproduction research still suffers from limitations imposed by the experimental design, methods, and the limited time allocated. Most gametogenetic studies are limited to 12-14 months, use a few colonies over reduced spatial scales, and sample only a few polyps of the colony. Recent research for example found that some gonochoric fungid species in Japan show bi-directional sex changes, with large individual polyps changing from male to female and vice versa year after year (Loya and Sakai 2008). My own research in Puerto Rico show that *Montastraea cavernosa* and *Dendrogyra cylindrus* are sequential gonochoric, changing sex over time.

Milleporid hydrocorals are overall gonochoric broadcast spawners that reproduce sexually by producing free-living gonochoric medusoids which release the gametes in the water column for external fertilization and embryogenesis of the planula larvae.

The table includes the most recent reproductive information for sexual pattern (G= gonochoric, H= Hermaphrodite, MP= mixed pattern), and mode of development (B= brooder, S= spawner, MM= mixed mode) known for Caribbean corals. There are at least 19 gonochoric species (14 of which spawn gametes into the water column, and 5 brood their well-developed larvae), and 38 hermaphrodites (14 broadcasters and 24 brooders). The rest of the species have been reported with mixed patterns and/or mode of development, or there is no information about their sexual reproduction. All hermaphroditic-spawning and gonochoric-spawning species have one gametogenetic cycle a year with 1-3 spawning events, mostly during late Summer early Fall, with a few species spawning during the Spring. Most hermaphrodite-brooding species usually have one or several oogenesis cycles with differential oocyte maturation over time, and a few spermatogenesis cycles, and show more than 3 brooding events, up to 10. This strategy compensates for the low number of larvae they can produce in each brooding event due to limited space in the gastro-coelenteron. The exception as off today, is the golf-ball coral *Favia fragum*, which has up to 10 gametogenetic cycles and broods year-around (Szmant 1986). There is still limited or no information for many Caribbean. Species, and some studies are limited in their design and sampling approach, spatial and temporal scales.

Growth morphologies, growth rates and “mean colony size”

Modular organisms, and specially corals, are highly plastic morphologically, changing growth direction and form in response to changes in environmental and/or biological pressures along their spatial/geographical distribution. The same species may show different colony morphologies along the depth gradient, from shallow, well-illuminated habitats where it could grow as a massive, dome-like colony, to bi-dimensional crusts, wide plates or skirt-like plates in low light, deeper habitats. This plasticity allows the colonies to enhance capture of low light quality and quantity and maximize photosynthetic rates. Exposure to waves and currents can produce different morphologies than in quiet lagoonal habitats within the same species. Morphological plasticity has been one of the main issues in some taxonomic unresolved taxa. The table presents the most common growth forms categorized as: **BO** = boulder, **MA** = massive, **SM** = sub-massive, **CR** = crustose, **PL** = thick plates, **BL** = thin blades /foliose, **CO** = Columns and **SP**= single polyps. A single species may have two or more of these categories. There are only two species which growth forms are basically columnar, *Dendrogyra cylindrus* and *Orbicella annularis*. However, *Meandrina meandrites, O. franksi* and *M. cavernosa* may be found growing vertically like a pinnacle.

Information on growth rates (cm/year) for at least 40 species was summarized from the relevant literature. There is limited or no information for the rest of the species. How fast a species grows was ranked as: (1) **Very fast** = species with max growth rates above 10 cm/year, (2) **Fast** = Species with max growth rates between 2 and 10 cm/year, (3) **Slow** = species with maximum growth rates between 0.5 and 2 cm/year, and (4) **Very Slow** = species with maximum growth rates below 0.5 cm/year.

Theoretically, modular organisms do not have biological-structural restrictions to how big they can grow. The continuous iteration of modules that adds new, “young” polyps to the colony constantly is adaptive because it increases survivorship and fecundity. Shape constraints and lack of intra-colony space for new calices could reduce growth and vertical expansion (Barnes 1970), but colonies could change direction and shape to overcome these limitations. Most species have slow-to-very-slow growth rates (0.1-2.0 cm/year) so, it will take hundreds to thousands of years for massive colonies for example, to reach significant sizes. The opposite is true for branching, fast-growing species like *Acropora cervicornis* and *A. palmata,* which can monopolize large reef areas in a few decades. Before the 1980’s, and for the previous 3000 years, acroporids were the most important Caribbean reef-building species, providing tridimensional structural relief and a diversity of habitats and refuges, while monopolizing most shallow, exposed reef habitats down to 10-15m, and well flushed lagoonal areas in the Caribbean region (Gladfelter 1982, Aronson and Precht 2001a,b; Weil 2003). These are weedy species that come and go frequently and that almost disappeared form Caribbean reefs after the WBD disease outbreak in the early 1980’s (Gladfelter 1982; Aronson and Precht 2001a).

If corals can grow “forever”, why don’t we see many gigantic massive or columnar colonies out there?, The answer is probably determined by a combination of factors such as; the low growth rates, the frequent partial mortality in colonies due to environmental stressors, competition, predation, disease, bleaching, and human direct and indirect impacts. Mean colony sizes were ranked mostly using published information and many decades of field observations of colonies of the different species in reefs across the wider-Caribbean. The ranking is based on the longest diameter as: (1) **Very small** = 1 - 10 cm in diameter, (2) **Small** = 10 - 30 cm in diameter, (3) **Medium** = 30 - 80 cm in diameter, (4) **Large** = 80 – 200 cm in diameter, and (5) = **Very Large =** > 200 cm in diameter.

Sediment susceptibility

There is some information related to the effect of sediment and tolerance to sedimentation for a few species in the Caribbean (Hubbard et al 1972, Hubbard 1973; Dodge et al.1974; Loya 1976; Hudson and Robbin 1980; Lasker 1980; Rogers 1983, 1990). Different coral species have evolved different mechanisms (i.e. tissue swallowing, cilia, mucus, skeletal structure, water spewing, etc.) to clean themselves of sediments (Stafford-Smith and Ormond, 1992), with some species being highly efficient and others not. However, besides the cleaning mechanisms, the sediment cleaning efficiency depends also on environmental factors such as water movement and clarity, sediment type and size (silt, clay, sand, calcium carbonate, etc.), colony shape and orientation, and how much energy is allocated to the process. In extreme sedimentary environments, or when dredging conditions exists nearby, all mechanisms might be overwhelmed by high rates of sedimentation, or larger particle sizes, and corals get smothered and killed. There are species that are highly tolerant to sedimentation and turbidity and do well in constantly murky and sedimentary environments (i.e. *S. siderea, S. intersepta, M. cavernosa, S. bournoni*, *Mycetophyllia* spp., *S. hyades*, *Scolynia* spp.). Water movement could not only affect the particle settling velocity, but also provide an additional force to compliment the active and passive removal processes. Colony orientation could also provide safety to species that have few or inefficient cleaning mechanisms (i.e. agariciids).

In near-shore locations, corals can be exposed to frequent sedimentation events. Corals will probably be exposed to a mixture of different sediment composition depending on location, distance from shore and proximity to river mouths (Furnas, 2003), and/or dredging activities (Dodge and Vaisnys 1977), from primarily calcium carbonate (i.e. the skeletal remains of animals and plants), to more terrestrially-derived silica-clastic sediment, clay etc. (Larcombe and Carter, 1998). The different types of sediments will vary in their density, weight, sphericity and angularity. In addition to different geochemical properties, the sediments will also differ in their organic and nutrient-related content, which can mediate effects once smothering has occurred (Weber et al., 2012). A number of studies have examined the difference in sediment rejection ability of corals in response to fine and coarse sediment, and rates of sedimentation. However, as noted in Jones et al. (2016), these studies have frequently used sands, whereas even close to a working dredge, the particle sizes are typically in the silt range (< 62 μm). Many studies examining the sediment shifting ability of corals have also used silicon carbide (carborundum) (Yonge, 1930; Bak and Elgershuizen, 1976; Stafford-Smith and Ormond, 1992; Junjie et al., 2014; Browne et al. 2015) and as with the use of sands, the relevance of these studies for impact prediction with dredging is uncertain.

Sediment susceptibility of each species was ranked as: **LOW (*)**= Species have efficient cleaning mechanisms (high mucus production, cilia, water ingestion, etc.), large polyps and or morphological traits and growth forms (branching, columnar, foliose, boulder-like) that aid in cleaning sediment and reducing sediment impact; **MODERATE-LOW** (**)= Some efficient cleaning mechanisms. Moderate-high mucus production, some morphological traits (medium-to-small shallow polyps, branches, vertical plates, etc.) that aid in reducing sediment impact; **MODERATE - HIGH (***)** = Moderately susceptible to sedimentation. Low cleaning efficiency with only moderate mucus production morphologies that usually trap some sediment. In exposed habitats: **HIGH** (****) = Highly susceptible to sedimentation, poor or no cleaning mechanisms, very low mucus production, morphologies that trap and retain sediment.

Bleaching susceptibility

Bleaching is the term used to describe the loss of all or some of the symbiotic algae and/or photosynthetic pigments by the animal host in marine environments. This results in that the underlying white calcium carbonate skeleton in corals for example, becomes visible through the now translucent tissue layer. Most photic cnidarians (corals, octocorals, hydrocorals, zoanthids, etc.) and other important reef invertebrates form mutualistic endosymbioses with the single celled dinoflagellate algae (*Symbiodinium* spp.). This association is usually obligate, with the host deriving over 80% of its energy budget from the algae photosynthesis (Muscatine and Porter 1977). The endosymbionts also play a vital role in the light-enhanced calcification of scleractinian corals (Chalker and Barnes 1990; Moya et al. 2006). In healthy corals, *Symbiodinium* typically occur at extremely high densities (>106 cells per cm2 coral tissue), but these densities go down significantly during bleaching.

Corals are known to bleach in response to a range of environmental stressors, but since the 1980's most large-scale coral mass-bleaching events have been predominantly driven by heat accumulation during prolonged thermal anomalies, which is now clearly related to human-induced global warming. Excess light seems to play a key additional role (Brown 1997; Hoegh-Guldberg 1999; Fitt et al. 2001; van Oppen and Lough 2018; Quigley et al. 2018). Small scale bleaching could result from a variety of other stressors such as low water temperatures, ocean acidification (Anthony et al. 2008), salinity, heavy metals, cyanide, herbicides, turbidity and other factors (reviewed in Baker and Cunning 2015). Furthermore, it has been hypothesized that elevated temperatures and other stressful events may trigger viral infections that contribute to coral bleaching and disease (Harvell et al. 2007; Vega Thurber et al. 2008; Vega Thurber and Correa 2011; Wilson et al. 2001; Levin et al. 2017; Weynberg et al. 2017). Severely bleached corals typically starve and die unless symbiont densities recover sufficiently rapidly to meet minimal phototrophic requirements and/or the coral has the ability to supplement its energy demands through increased heterotrophy (Grottoli et al. 2006; Anthony et al. 2009; Hoogenboom et al. 2012). The effect of coral bleaching has major consequences for reef productivity, reef growth, and biodiversity (McClanahan et al. 2018).

Thermal stress on coral reefs has clearly increased over the past century (Heron et al. 2016). As global temperatures continue to rise, the threat to coral reefs is increasing significantly. Mass bleaching events have become more frequent and intense and extend over larger spatial scales impacting entire reef systems and many taxa compared to the more localized events of the past. All five global bleaching events (1983, 1987, 1998, 2010, 2016) occurred during or just after moderate or major El Niño years. Other important but localized events like in 2003 and 2005 in the Caribbean also coincided with moderate El Niño (Oliver et al. 2018). Unprecedented and prolonged ocean warming triggered what is now been widely referred to as the "worst bleaching ever", starting in 2014, and extending well into the 2017's. The length of the event prevented corals in many areas of the world to recover prior to experiencing another thermal stress and bleaching the following year (van Hooidonk et al. 2016; Hughes and Kerry 2017). Large-scale bleaching events have resulted in extensive mass coral mortalities, mostly in the Indo-Pacific, and it is now a critical global threat to coral reefs (Baker et al. 2008; Heron et al. 2016; Hughes et al. 2017; Oliver et al. 2018).

Coral reefs develop well within a fairly narrow range of environmental conditions (water temperatures, light, salinity, nutrients, bathymetry, and the aragonite saturation state of seawater) (Buddemeier and Kinzie 1976; Kleypas et al. 1999; Hoegh-Guldberg 2005). Their natural environment, at the interface of land, sea, and the atmosphere, can vary quickly and can become highly stressful. Reef organisms have evolved strategies to cope with most environmental disturbances (such as tropical cyclones, thermal anomalies, etc.), and given enough time (good, stable environmental conditions) between disturbances, reefs recover and regrowth after the impact (Buddemeier et al. 2004). Early studies in the 1970's demonstrated just how close (within 1–2 °C) reef-building corals usually live to their upper thermal tolerance limits and how subtle rises in temperature often led to bleaching (Coles et al. 1976; Jokiel and Coles 1977; Glynn and D'Croz 1990). These studies and others have identified that temperature thresholds at which corals bleach vary with the ambient water temperatures on each reef, such that corals have adapted to their local environmental conditions over long timescales (Oliver et al. 2018).

The influence of symbiont identity and diversity on fitness of the coral host has been increasingly recognized. To a large extent, physiological characteristics of distinct symbiont types have been inferred from correlative studies (Quigley et al. 2018). For example, zonation of *Symbiodinium* types over light gradients within colonies and between shallow and deep colonies of *Orbicella* spp. suggests that distinct symbionts have distinct light sensitivities (Rowan and Knowlton 1995; Rowan et al. 1997; Toller et al. 2001a, b; Kemp et al. 2015). Observations of patchy bleaching within *Orbicella* colonies during a natural bleaching event further suggest that variability in bleaching tolerances of the different *Symbiodinium* types, or that different clades of *Symbiodinum* seems to have different temperature tolerances to bleaching. Bleaching o the other hand, may be a mechanism to change *Symbiodinium* communities inside host tissues in favor of a community that is better adapted to the changed environmental conditions (Buddemeier and Fautin 1993; Baker 2001; Baker et al. 2004). However, communities in some colonies may change in the absence of visible bleaching (Thornhill et al. 2006a, b).

The response of individual coral colonies may be shaped by previous experience (Buddemeier and Fautin 1993; Oliver and Palumbi 2011; McClanahan 2017). Individuals can also respond to bleaching by changing the relative abundance of high-temperature-resistant symbiont strains making individuals less susceptible to subsequent bleaching events (Baker 2003; Baker et al. 2004; Oliver and Palumbi 2011). Consequently, there is increasing evidence that some corals can adjust to global warming, and, therefore, projections of the future state of coral reefs need to take adaptation and acclimation into account (Logan et al. 2014). Predictions based on climate models and thermal tolerance of corals suggest regular widespread catastrophic bleaching within the next 15–25 years (Hoegh-Guldberg 1999; Donner et al. 2005; Logan et al. 2014; van Hooidonk et al. 2016). However, climate models deal with large-scale atmospheric and oceanic processes, which in themselves are highly complex with many parameters and feedback loops that are difficult to quantify (van Oppen et al. 2018).

The most detailed descriptions of the taxa affected by bleaching come from the Caribbean where numerous species bleached in response to higher than usual sea temperature in 2005 and 2010 (Miller et al. 2006; Weil et al. 2009a; Rogers et al. 2009; McClanahan et al. 2008). Five species of hydrozoan (100% of the species pool), 60 species of scleractinians (90% of the species pool), and 30 octocoral species (20% of the species pool) bleached along with other cnidarians and sponges (McClanahan et al. 2018; Prada et al. 2010). Sub-lethal effects on individual coral reef organisms following bleaching include reduced reproductive output, reduced growth, and increased susceptibility to diseases and other disturbances (Lesser et al. 2007; McClanahan et al. 2018).

Bleaching susceptibility for the different species was ranked based on most published information on intensity (pale to white) and partial (focal) or total colony affected, prevalence levels and partial or total colony mortality during the documented Caribbean bleaching events (McClanahan et al 2018) and personal observations through several bleaching events in the Caribbean. Classification is as follows: **LOW** (*) = High resistance. Partial/total bleaching only during extreme thermal events (> 10 DHW), very low prevalence and usually no partial or colony mortality; **MODERATE-LOW** (**) = Colonies loose coloration (pale) during medium-high thermal anomalies (6-9 DHW). Low bleaching prevalence and colonies may suffer partial mortality. **MODERATE-HIGH (***) =** Colonies bleaching frequently even during moderate thermal anomalies (4-6 DHW), moderate to high prevalence levels, many colonies turn white, some partial and colony mortality**. HIGH (****)** = Many colonies bleach frequently, even at low thermal anomalies (2-4 DHW). High prevalence during bleaching events, most colonies white and usually high partial and/or colony mortality.

Disease susceptibility

Coral reef mass mortalities appear related to the more frequent, intensive, and extensive thermal anomalies associated with global climate change (GCC), which has triggered historically, unprecedented bleaching events and lethal disease outbreaks affecting foundation, keystone, and commercially important species in tropical and temperate coastal environments (Harvell et al. 1999, 2002, 2007, 2009; Aronson and Precht 2001a; Rosenberg and Loya 2004; Miller et al. 2006; Bruno and Selig 2007; Hoegh-Guldberg et al. 2007, 2017; Carpenter et al. 2008; Croquer and Weil 2009; Lough and van Oppen 2009; Miller et al. 2009; Weil et al. 2009, 2017; Weil and Rogers 2011; Altizer et al. 2013; Randall et al. 2014; Maynard et al. 2015; Woodley et al. 2016; Lafferty and Hoffman 2016; Hughes et al. 2017). Unprecedented and prolonged ocean warming triggered the longest and deadliest bleaching on record, from 2014 to 2017 (van Hooidonk et al. 2016; Hughes and Kerry 2017).

Concurrent with this, deadly disease outbreaks affecting corals and other invertebrates were reported from tropical to temperate regions. A presumed new "white-plague type" disease called Stony Coral Tissue Loss Disease (SCTLD) (Meyer et al. 2019), killing large numbers of corals in a short time, was reported from southeastern Florida in 2014 (Precht et al. 2016; Walton et al. 2018), and unprecedented mass mortalities of many species of sea stars along the northwest and northeast coasts of the USA (Fuess et al. 2015), and several other disease outbreaks affecting oysters, lobsters, crabs, and other important economic species (Burge et al. 2014; Groner et al. 2016).

The problem is exacerbated by local/regional, anthropogenic stressors such as pollution, coastal development, dredging, uncontrolled "ecotourism", overfishing, etc. (Burge et al. 2014; Jackson et al. 2014). Current estimates of negative changes in shallow coral reefs are two to three orders of magnitude faster than those during the glacial cycles of the past 420,000 years (Hoegh-Guldberg et al. 2007). It is predicted that the top 100 m of the ocean will become 0.6–2.0 °C warmer by the end of this century (IPCC 2014). This raises concern since the most diverse and productive marine ecosystems lay within this depth interval, including all shallow coral reefs and an extensive portion of upper-mesophotic coral ecosystems (MCEs) (Weil 2019).

The Caribbean is considered as a disease "Hot Spot" due to the large number of diseases affecting reef organisms, the frequent emergence of new diseases, and the frequent disease outbreaks (Weil et al. 2006; Weil and Rogers 2011). The major community structure and function decline was marked by two region-wide, concurrent, highly virulent disease epizootics in the early 1980's. These events almost wiped out two foundation scleractinian species (*Acropora palmata* and *A. cervicornis*), and the keystone sea urchin *Diadema antillarum*. White band disease (WBD) affected the acroporids and was caused by a complex of vibrio bacteria (Gil-Agudelo et al. 2006). The *Diadema* mass mortality had all the trademark characteristics of a virulent, transmissible, bacterial or viral infection, but the putative pathogen (s), was never identified (Lessios 2016). Populations of both acroporids and sea urchins suffered over 95% mortalities throughout the wider Caribbean (Gladfelter 1982; Lessios et al. 1984a,b; Aronson and Precht 2001a; Lessios 2016; Weil et al. 2005), followed by a cascade of ecological consequences (i.e. significant loss of live coral cover, primary productivity, spatial complexity, biodiversity and fecundity, loss of ecological functions, increase in algal cover and biomass, etc.), finally ending in a shift from coral- to algal-dominated communities and the loss of ecological services to other tropical marine communities and to human beings (Aronson and Precht 2001a; Weil and Rogers 2011). Several other disease-induced, mass mortalities of massive, plate and nodular reef-building coral genera, and other important cnidarians in the last 30 years resulted in additional significant loss of biomass (live coral tissue), reef structure, and diversity throughout the region (Miller et al. 2009; Rogers et al. 2009; Weil et al. 2009a; Weil and Rogers 2011; Bastidas et al. 2012; Jackson et al. 2014). Significant loss of fecundity due to the loss of live coral tissue (polyps), overfishing of herbivorous fish and lack of recovery of *Diadema,* together with the continuous deterioration of local environmental conditions and Global Warming is presumably impairing the natural (and sometimes assisted) recovery of damaged coral communities across the Caribbean (Hughes and Tanner 2000; Weil et al. 2005; Jackson et al. 2014; Tuohy et al. 2019).

Immunity is an important biological property that promotes survivorship, fitness, and adaptability in organisms. Invertebrates, including cnidarians, possess innate, variable, and adaptive immune responses, which help them to defend and adapt against environmental stress, opportunistic infections and disease. Like all physiological functions, maintenance of the immune system and function requires energy and resources, which in stressful conditions, involve trade-offs against energetic investment in other important functions such as growth, feeding, reproduction, etc. Several innate immunity mechanisms, including the ability to discriminate allogenic from xenogenic tissues, have been described for corals and octocorals (Mydlarz et al. 2008, 2010; Burge et al. 2013). Although limited in response capabilities, innate immune responses in cnidarians include production and movement amaebocytes and effector enzymes, small molecules that selectively bind to a protein regulating its biological activity. In naturally infected sea fans with dense amoebocytes, for example, a concurrent increase in prophenoloxidase (PPO) activity occurred. This is linked to the production of melanin that is deposited along the axial skeleton to prevent the fungal hyphae (aspergillosis) from entering the surrounding tissue (Petes et al. 2003; Mullen et al. 2006; Mylardz et al. 2008). Several histological studies have also illustrated a series of inflammatory responses of amoebocytes to infections in *G. ventalina* (Mydlarz et al. 2008). Organic extracts of most Caribbean gorgonians lack potent, broad-spectrum antibacterial activity, suggesting that the inhibition of bacterial growth is not the primary function of gorgonian secondary metabolites (Jensen et al. 1996). Antibiotic production by associated, mutualistic bacteria living in the mucus layer is probably an effective way of preventing other bacteria to compete for the resources of the energetic and protein rich coral mucus.

Resistance (susceptibility) to each of the different diseases is determined by the innate immune system of the host, the virulence of the pathogen, both of which vary across individuals, populations and species, and the environmental conditions which can vary spatially and temporarily. Establishing levels of disease susceptibility for each coral species is therefore both difficult and problematic. The ranking can vary across populations and species as well as spatially and temporarily. The disease susceptibility rankings presented in the table were based on the published information about the number of diseases affecting each particular species, the population/species disease prevalence and levels of mortality reported during diseases outbreaks, in different localities and over time. This assessment also includes my personal experience after 20 years observing the emergence and impact of coral reef diseases across the wider-Caribbean. The disease susceptibility ranking is: **LOW (*)** (**=** highly Resistant)= Never or rarely diseased, and when diseased, very low prevalence (0-5%) and tissue/colony mortality during disease outbreaks; **MODERATE-LOW** (**) susceptible to one or a few diseases only; low to moderate prevalence values (5-10%) during disease outbreaks, low - moderate tissue mortality only; **MODERATE-HIGH** (***) = Susceptible or several diseases. Frequently diseased with medium-high prevalence levels (10-25%) during outbreaks, high partial and/or colony mortality; **HIGH** (****) = Susceptible to many diseases, consistently diseased with significantly high prevalence levels (>25%) and tissue and colony mortality during outbreaks.

Appendix Tables

Tables include (Taxa are in the same order in each table, sorted by family and then genus):

Legends
Table 1: Taxa phylogeny and description
Table 2: Traits (depth range, life history strategy, reproduction, growth rate, growth form)
Table 3: Disease Susceptibility
Table 4: BCG Attributes and Pathogenic Diseases
Table 5: Distribution and Description

Table: Legends

SP#: EM= Ecomorphs. HYB= Hybrid. Shallow, non-zooxanthelated, small, cryptic spp. (Caryophyllidae) not included.

Color codes	
(light orange)	Threatened or endangered species
(pink)	Taxonomic status not fully resolved
(light green)	Recently described new species
(grey)	Invalid species??
(tan)	Invasive species
(lavender)	Hydrocorals
(blue)	Wide depth distribution including mesophotic habitats

BCG ATTRIBUTES	Description	Ranking
1	Pristine-good	low
2	good	Moderate-low
3	Somehow impacted	Moderate
4	Impacted	Moderate high
5	Highly impacted - bad	High
6	Very bad	

Life History Strategies (Criteria for ranking from the literature and personal observations and experimentation)
Weedy Species (W)= Small branching and submassive colonies of mostly brooding spp. Small corallites, low fecundity but high survivorship. High variability in LH traits. Competitors (C)= Large, branching, plating, fast growing spp. in shallow habitats. Broadcasters. High mortalities and susceptible to bleaching and fragmentation Stress Tolerant (S):. Slow growing, dome- shaped, massive, platy, Submassive growth Broadcaster with high fecundity Generalist (G)= mixed C. S, and W strategies. Domed, platy, submassive colonies, slow growth, Brooders or broadcasters.

Reproductive pattern-mode	**Gametogenesis**	**Spawning**	**Spawning-Brooding season:**
Sexual Pattern G = gonochoric H= hermaphroditic Reproductive Mode B= Brooder S= Spawner (broadcaster) Mixed pattern (MP) Mixed mode (MM) ? = Unknown	Number of gametogenetic cycles per year	Number of spawning events per reproductive season	SU= Summer FA= Fall SP= Spring WI = Winter

Growth form	**Growth rates**	**Growth**	**Size**
BO = boulder **MA** = massive **SM** = sub-massive **CR** = crustose **PL** = plates **BL** = thin blades /foliose **CO** = Columns **SP** = Single polyp Single species might show different growth forms depending on habitat, competition and environment	Data on growth rates of the different species is from the literature	**Very fast** = species with max growth rates above 10 cm/year. **Fast** = Species with max growth rates between 2 and 10 cm/year. **Slow** = species with maximum growth rates between 0.5 and 2 cm/year. **Very Slow** = Species with maximum growth rates below 0.5 cm/year	**Very small** = 1 - 10 cm in diameter **Small** = 10 - 30 cm in diameter **Medium** = 30 - 80 cm in diameter **Large** = 80 - 200 cm in diameter **Very Large** = > 200 cm in diameter

Ranking	Sediment Susceptibility	Bleaching Susceptibility	Disease Susceptibility
LOW (*)	Species have efficient cleaning mechanisms (high mucus production, cilia, water ingestion, etc.), large polyps and or morphological traits and growth forms (branching, columnar, foliose) that aid in reducing sediment impact	Highly resistant species. Partial/total bleaching only during extreme thermal events (> 10 DHW), very low prevalence and usually no partial or colony mortality	Highly Resistant. Never or rarely diseased, and when diseased, very low prevalence (0-5%) and tissue/colony mortality during disease outbreaks
MODERATE-LOW (**)	Some efficient cleaning mechanisms. Moderate-high mucus production, some morphological traits (medium-to-small shallow polyps, branches, vertical plates, etc.) that aid in reducing sediment impact.	Colonies loose coloration (pale) during medium-high thermal anomalies (6-9 DHW). Low bleaching prevalence and colonies may suffer partial mortality	Susceptible to one or a few diseases only; low to moderate prevalence values (5-10%) during disease outbreaks, low - moderate tissue mortality only
MODERATE - HIGH (***)	Moderately susceptible to sedimentation. Low cleaning efficiency with only moderate mucus production morphologies that usually trap some sediment. In exposed habitats.	Colonies bleaching frequently even during moderate thermal anomalies (4-6 DHW), moderate to high prevalence levels, many colonies turn white, some partial and colony mortality.	Susceptible or several diseases. Frequently diseased with medium-high prevalence levels (10-25%) during outbreaks, high partial and/or colony mortality.
HIGH (****)	Highly Susceptible, poor or no cleaning mechanisms, very low mucus production, morphologies that trap and retain sediment.	Many colonies bleach frequently, even at low thermal anomalies (2-4 DHW). High prevalence during bleaching events, most colonies white and high partia/ colony mortality	Susceptible to many diseases, consistently diseased with significantly high prevalence levels (>25%) and tissue and colony mortality during outbreaks.

Criteria for ranking derived from the literature and personal observations and experimentation

Ranking	Sediment Susceptibility	Bleaching Susceptibility	Disease Susceptibility
BCG 1	Highly resistant to sedimentation. Efficient cleaning mechanisms and/or favorable morhologies.	Highly resistant, only bleach under extreme, long thermal anomalies. Colonies usually show pale coloration.	Low susceptibility. Almost never diseased. Low prevalence (0-5%) and no little tissue mortality during ourbreaks.
BCG 2 - 3	Usually affected by high sedimentation events. Low sediment-related mortality.	Do not bleach frequently, only under high thermal anomalies. Colonies mostly pale, with a few white.	susceptible to one or a few diseases only; low to moderate prevalence values (5-10%) during disease outbreaks, low - moderate tissue mortality only.
BCG 3 - 4	Usually affected by sedimentation. Some sediment- related mortality	Susceptible, bleaching frequently. Some colonies turn white.	Moderate-to-high susceptibility to several diseases. Frequently diseased, high prevalence (10-25%) during outbreaks and high partial and/or colony mortality
BCG 5	Highly sudceptible to sedimentation. Frequent sedimentation-related mortality	Highly suceptible to increase/decrease temps. Most colonies turn white.	Susceptible to many diseases, consistently diseased with significantly high prevalence levels (>25%) and tissue and colony mortality during outbreaks.

Criteria for ranking derived from the literature and personal observations and experimentation

PATHOGENIC DISEASES

NOTE: Disease is a dynamic process so, it is difficult to characterize into definitive categories or hierarchies These will change spatially and temporarily as host immune responses and pathogen virulence varies and adjust, and/or inducing environmental factors change. A population/species could be highly susceptible to one or two diseases, showing high prevalence and high tissue and/or colony mortality, and moderately susceptible or resistant to other diseases, showing low prevalence and mortality (i.e Acrporids with WBD, WPX, CCI; *Orbicella* spp. with WPD, CYBD, DSD). Others that were highly susceptible to one or many diseases in the past, no have resistant populations developed from the survivors (right genetic combination). These, may or may not be susceptible to newly emergent diseases (new pathogens).

Most Common coral diseases
BBD = Black Band Disease
WBD= White Band Disease
WPD = White Plague Disease
CYBD= Caribbean Yellow Band Disease
DSD = Dark Spots Disease
WPX = White Pox/White Patches/ Serriatosis
GAN = Growth Anomalies (Hyperplasias and hypoplasias)
CCI= Caribbean Ciliate Infection
RBD = Red Band Disease
IMS = Intra costal Mortality Syndrome
SCTLD = Stony Coral Tissue Loss Disease
OTH = Other syndromes not characterized

BCG equivalent

(*) = 1 = Very low susceptibility = Highly resistant. Rarely showing disease signs
Very low prevalence and mortality during outbreaks.
(**) = 2-3 = Moderate-low. Susceptible to one or few diseases;
low to moderate prevalence values during outbreaks, low - moderate tissue mortality.
(***) = 3-4= Moderate-high. Colonies frequently showing signs of disease.
High prevalence and mortality during outbreaks.
(****) = 5 = low resistance. Consistently diseased, susceptible to many diseases.
High prevalence during outbreaks. High mortality.

BCG Coding

1-2 (*) = Very low to low - (Highly resistant). Rarely showing disease signs of one or a couple of the common diseases
Very low prevalence and mortality during outbreaks.
3-4 (**) = moderate-low - intermediate. Few colonies diseased regularly.
Intermediate prevalence’s and low mortality during outbreaks
5 (***) = high (low resistance) Colonies frequently showing signs of disease.
High prevalence and mortality during outbreaks.

Table 2: Taxa Phylogeny and Description

SPECIES NAME	SP #	FAMILY	FORMER/OTHER USED NAME	COMMON ENGLISH NAME	COMMON SPANISH NAME
Stephanocoenia intersepta	1	Astrocoeniidae	*Stephanocoenia michelini*	Blushing star coral	Coral estrella poligonal
Acropora cervicornis	2	Acroporidae		staghorn coral	Cuerno de venado
Acropora sp.	EM	Acroporidae	*A. cervicornis*	Thick staghorn coral	Cuerno de venado grueso
Acropora palmata	3	Acroporidae		elkhorn coral	Cuerno de alce
Acropora prolifera	HYB	Acroporidae	*A. cervicornis*	fused staghorn	Cuerno de venado hybrido
Undaria tenuifolia	4	Agariciidae	*Agaricia agaricites*	Thin leaf lettuce coral	Coral lechuga bifacial delgado
Undaria agaricites	5	Agariciidae	*Agaricia agaricites*	Low relief lettuce coral	Coral lechuga incrustante
Undaria humilis	6	Agariciidae	*Agaricia agaricites f. humilis*	Low relief lettuce coral	Coral lechuga incrustante
Undaria purpurea	7	Agariciidae	*Agaricia agaricites f. purpurea*	Lettuce coral	Coral lechuga intrincada
Undaria carinata	EM	Agariciidae	*Agaricia agaricites f. carinata*	Lettuce coral	Coral lechuga compacta
Undaria crassa	EM	Agariciidae	*Agaricia agaricites f. crassa*	Lettuce coral	Coral lechuga bajo relieve
Undaria danae	8	Agariciidae	*Agaricia agaricites f. danae*	Bifacial lettuce coral	Coral lechuga bifacial grueso
Undaria pusilla	9	Agariciidae	*Agaricia agaricites, A. fragilis*	Small criptic lettuce coral	Coral lechuga criptico pequeno
Agaricia fragilis	10	Agariciidae	*A. agaricites*	Fragile saucer coral	Coral lechuga plato fragil
Agaricia fragilis	EM?	Agariciidae	*Agaricia fragilis*	Fragile saucer coral	Coral lechuga plato fragil
Agaricia lamarcki	11	Agariciidae		Whitestar sheet coral	Coral de estrellas blancas
Agaricia grahamae	12	Agariciidae	*Agaricia sp.*	Dimpled sheet coral	Coral plato incrustado
Agaricia undata	13	Agariciidae		Scroll plate coral	Coral plato enrollado
Leptoseris cailleti	14	Agariciidae	*Helioceris cailleti*	Foliose lettuce coral	Coral lechuga foliosa

Table 2: Taxa Phylogeny and Description

SPECIES NAME	SP #	FAMILY	FORMER/OTHER USED NAME	COMMON ENGLISH NAME	COMMON SPANISH NAME
Helioceris cucullata	15	Agariciidae	*Leptoseris cucullata*	Sunray lettuce coral	Coral lechuga rayo de sol
Dendrogyra cylindrus	16	Meandrinidae		Pillar coral	Coral pilar o columnar
Eusmilia fastigiata	17	Meandrinidae		Smooth flower coral	Coral flor amarilla
Eusmilia fastigiata f. flagellata	EM	Meandrinidae	*Eusmilia fastigiata*	Smooth flower coral	Coral flor amarilla
Dichocoenia stokesii	18	Meandrinidae		Elliptical star coral	Coral estrella eliptica
Dichocoenia stellaris	EM	Meandrinidae	*Dichocoenia stokesii*	Uniserial elliptical	Coral estrella eliptica
Meandrina meandrites	19	Meandrinidae	*Meandrina memorialis*	Maze coral	Coral laberinto
Meandrina Jacksoni	20	Meandrinidae	*Meandrina meandrites, M. memorialis*	White valley maze coral	Coral laberinto valles blancos
Meandrina danae	21	Meandrinidae	*Meandrina brasiliensis*	Butterprint rose coral	Coral laberinto pequeno
Meandrina sp.	EM	Meandrinidae	*Meandrina meandrites*	Maze coral	Coral laberinto
Goreaugyra memorialis	?	Meandrinidae	*Meandrina memorialis*	Deep Columnar Maze coral	Coral laberinto profundo
Colpophyllia natans	22	Mussidae		Boulder brain coral	Coral cerebro valle angosto
Colpophyllia amaranthus	23	Mussidae	*Colpophyllia natans*	Brain coral	Coral cerebro de valle ancho
Colpophyllia breviserialis	EM	Mussidae	*Colpophyllia natans*	Brain coral	Coral cerebro de valles cerrados
Pseudodiploria clivosa	24	Mussidae	*Diploria clivosa*	Knobby brain coral	Coral cerebro noduloso
Pseudodiploria strigosa	25	Mussidae	*Diploria strigosa*	Symmetrical brain coral	Coral cerebro simetrico
Diploria labyrinthiformis	26	Mussidae		Grooved brain coral	Coral cerebro con surcos
Favia fragum	27	Mussidae		Golfball coral	Coral bola de golf

Table 2: Taxa Phylogeny and Description

SPECIES NAME	SP #	FAMILY	FORMER/OTHER USED NAME	COMMON ENGLISH NAME	COMMON SPANISH NAME
Manicina areolata	28	Mussidae		Rose coral	Coral Rosa
Manicina mayori	EM	Mussidae	*Manicina areolata*	Rose coral	Coral Rosa Grande
Isophyllia sinuosa	29	Mussidae		Sinuos cactus coral	Coral cactus sinuoso
Isophyllia rigida	30	Mussidae	*Isophyllastrea rigida*	Rough cactus coral	Coral cactus rugoso
Isophyliia multiflora	EM	Mussidae	*Isophyliia sinuosa*	Sinuos cactus coral	Coral cactus sinuoso
Mycetophyllia ferox	31	Mussidae		Rough cactus coral	Coral cactus colinas continuas
Mycetophyllia aliciae	32	Mussidae		Knooby cactus coral	Coral cactus valle amplio
Mycetophyllia lamarckiana	33	Mussidae		Ridged cactus coral	Coral cactus valle ancho
Mycetophyllia danana	34	Mussidae		Deep valley cactus coral	Coral cactus valle profundo
Mycetophyllia resii	35	Mussidae		Ridgeless cactus coral	Coral cactus plano
Scolymia cubensis	36	Mussidae		Solitary disk corals	Coral solitario pequenio
Scolymia lacera	37	Mussidae		Solitary disk corals	Coral solitario grande
Scolymia wellsi	38	Mussidae	*Scolymia cubensis*	solitary disk corals	Coral solitario
Scolymia nsp.	EM	Mussidae	*Scolymia cubensis*	Solitary red coral	Coral solitario rojo
Mussa angulosa	39	Mussidae	*Scolymia lacera*	Atlantic mushroom coral	Coral hongo polipos grandes
Orbicella annularis	40	Merulinidae	*Montastraea annularis*	Lobed star coral	Coral estrella columnar
Orbicella faveolata	41	Merulinidae	*Montastraea faveolata*	Mountainous star coral	Coral estrella masivo
Orbicella franksi	42	Merulinidae	*Montastraea franksi*	Boulder star coral	Coral estrella rugoso
Montastraea cavernosa	43	Montastraeidae		Great star coral	Coral estrella calices grandes

Table 2: Taxa Phylogeny and Description

SPECIES NAME	SP #	FAMILY	FORMER/OTHER USED NAME	COMMON ENGLISH NAME	COMMON SPANISH NAME
Montastraea nsp.	EM	Montastraeidae	*Montastraea cavernosa*	Large polyped star coral	Coral estrella calices grandes
Porites astreoides	44	Poritidae		Mustard hill coral	Coral mostaza
Porites colonensis	45	Poritidae	*Porites astreoides*	Honeycom plate coral	Coral panal plato
Porites porites	46	Poritidae		Clubtip finger coral	Coral dedo grueso
Porites furcata	47	Poritidae	*Porites porites*	Branching finger coral	Coral dedo
Porites divaricata	48	Poritidae	*Porites porites*	Thin finger coral	Coral dedo fino
Porites nsp.	EM	Poritidae	*Porites branneri*	Blue crust coral	Coral azul crustoso
Madracis decactis	49	Pocilloporidae		Ten ray star coral	Coral de 10 septos noduloso
Madracis formosa	50	Pocilloporidae	*Madracis decactis*	Eight-ray star coral	Coral de ocho septos ramoso
Madracis carmaby	51	Pocilloporidae	*Madracis formosa*	Ten ray finger coral	Coral de diez septos ramoso
Madracis pharensis f luciphogous	52	Pocilloporidae	*Madracias pharensis*	Ten ray crustose coral	Coral de diez septos incrustante
Madracis pharensis f. luciphylla	EM	Pocilloporidae	*Madracis pharensis*	Ten ray massive coral	Coral de diez septos masivo
Madracis senaria	53	Pocilloporidae	*Madracias pharensis*	Six-ray star coral	Coral de seis septos submasivo
Madracis auretenra	54	Pocilloporidae	*Madracis mirabilis, M. asperula*	Yellow pencil coral	Coral lapiz amarillo
Madracis asperula	EM	Pocilloporidae	*Madracis mirabilis*	Deep yellow pencil coral	Coral lapiz profundo
Madracis myriaster	55	Pocilloporidae	*Madracis mirabilis*	Deep yellow pencil coral	Coral lapiz profundo
Oculina diffusa	56	Oculinidae		Diffuse ivory coral	Coral marfil difuso
Oculina varicosa	57	Oculinidae	*Oculina diffusa*	Large ivory coral	Coral marfil largo

Table 2: Taxa Phylogeny and Description

SPECIES NAME	SP #	FAMILY	FORMER/OTHER USED NAME	COMMON ENGLISH NAME	COMMON SPANISH NAME
Oculina valecienesi	58	Oculinidae		Small ivory coral	Coral marfil corto
Oculina robusta	59	Oculinidae		Robust ivory coral	Coral marfil robusto
Siderastraea siderea	60	Siderastreidae		Massive starlet coral	Coral estrellado masivo
Siderastrea radians	61	Siderastreidae		Lesser starlet coral	Coral estrellado pequeno
Siderastrea stellata	EM	Siderastreidae	*Siderastrea siderea*	Lesser starlet coral	Coral estrellado submasivo
Cladocora arbuscula	62	"Incertae sedis"		Tube coral	Coral tubo
Solenastrea bournoni	63	"Incertae sedis"		Smooth star coral	Coral estrella liso
Solenastrea hyades	64	"Incertae sedis"		Knobby star coral	Coral estrella noduloso
Tubastraea coccinea	65	Dendrophylliidae	*Tubastraea aurea; T. tenuillamellosa*	Orange cup coral	Coral copa naranja
Tubastraea micranthus	66	Dendrophylliidae		Green cup coral	Coral copa verde ramoso
Tubastraea aurea	EM	Dendrophylliidae	*T. tenuillamellosa, T. coccinea*	Orange Cup Coral	Coral copa naranja
Millepora alcicornis	1	Milleporidae		Branching fire hydrocoral	Coral de fuego ramoso
Millepora complanata	2	Milleporidae	*Millepora alcicornis*	Blade fire hydrocoral	Coral de fuego plano
Millepora striata	3	Milleporidae		Striated fire hydrocoral	Coral de fuego estriado
Millepora squarrosa	4	Milleporidae	*Millepora complanata*	Box fire hydrocoral	Coral de fugo submasivo
Stylaster roseus	5	Milleporidae		Rose lace coral	Hydrocoral rosado

Table 3: Traits

SPECIES NAME	Depth Range (m)	Life Hist-ory Strat-egy	REPRO-DUCTION pattern-mode	Yearly Gameto-genesis	Spawning/ brooding		Growth form	Growth rate (cm/year)	Growth	Mean size
					events	season				
Stephanocoenia intersepta	5 - 35	G	G - S	1	1-2	SU	MA-CR	0.1 - 2	Slow-fast	Med - Lg
Acropora cervicornis	0 - 20	C	H - S	1	1-2	SU	BR	4 - 37	Very fast	Lg - V. Lg
Acropora sp.	0 - 10	C	H - S	1	1-2	SU	BR	8 - 25	Very fast	Lg - V. Lg
Acropora palmata	0 - 20	C	H - S	1	1-2	SU	BR-CR	2.5 - 20	Very fast	Lg - V. Lg
Acropora prolifera	0 - 10	C	H - S	1	1-2	SU	BR	7 - 32	Very fast	Lg - V. Lg
Undaria tenuifolia	0 - 20	W	? - B	1	>1	SP-SU-FA	FO-BL	0.8	Slow	Med - Lg
Undaria agaricites	0 - 50	W	G - MP - B	1	>6	SP-SU-FA	SM-CR	0.08 -0.2	Very Slow	Sm
Undaria humilis	0 - 25	W	G - MP- B	1	>6	SP-SU-FA	PL-CR	?	Very Slow	Sm - Med
Undaria purpurea	2 - 15	W	H - B	1	>1	SU-FA?	PL-CR	?	Very Slow	Med
Undaria carinata	2 - 15	W	? - B	1	?	?	FO-BL	?	?	Sm
Undaria crassa	3 - 15	W	? - B	1	?	?	FO-BL	?	?	Sm
Undaria danae	2 - 15	W	? - B	1	>1	SU-FA?	SM-FO	0.8 - 1.16	Slow	Med - Lg
Undaria pusilla	0 - 10	W	? - B	1	>1	SU-FA?	CR-FO	?	Slow	V. Sm
Agaricia fragilis	10 - 50	W	? - B	1	>1	SU-FA?	CR-FO	?	?	Sm
Agaricia fragilis	5 - 30	W	? - B	1	>1	?	CR-FO	?	?	Sm
Agaricia lamarcki	10 - 80	W	G - B	1	>1	SU-FA	PL-CR	0.4 - 0.6	Slow	Lg - V. Lg
Agaricia grahamae	30 - 80?	W	? - B	1	?	?	PL-CR	?	?	Lg - V. Lg
Agaricia undata	20 - 80?	W	? - B	1	?	?	PL-CR	?	?	Lg - V. Lg
Leptoseris cailleti	35 - 80?	W	? - ?	?	?	?	FO-BL	?	?	Sm - Med
Helioceris cucullata	5 - 50?	W	? - B	?	?	?	PL-CR	?	?	Sm - Med
Dendrogyra cylindrus	1 - 20	G	G - S	1	1	SU	CO-CR	0.5 - 1.8	Slow	Lg - V. Lg

Table 3: Traits

SPECIES NAME	Depth Range (m)	Life Hist-ory Strat-egy	REPRO-DUCTION pattern-mode	Yearly Gameto-genesis	Spawning/ brooding		Growth form	Growth rate (cm/year)	Growth	Mean size
					events	season				
Eusmilia fastigiata	5 - 25	G	G - S	1	1	SU	BR	0.7	Slow	Med
Eusmilia fastigiata f. flagellata	5 - 15	G	G - S	1	1-2	SU	BR	0.7	Slow	Med
Dichocoenia stokesii	5 - 20	G	G - S	1	1-2	SU-FA	SM-CR	0.2	Very Slow	Med
Dichocoenia stellaris	10 - 20	G	? - B	>1	?	SU-FA	SM-CR	0.2	Very Slow	Med
Meandrina meandrites	3 - 40	W	MP - B	1	>1	SU-FA	MS-SM-PL-CO	0.1 - 0.3	Very Slow	Med
Meandrina Jacksoni	3 - 25	W	G - S	1	1-2	SU-FA	SM-MA-CR-PL	0.1- 0.3	Very Slow	Med
Meandrina danae	10 - 30	W	MP - S	1	1-2	SU-FA	SM	?	Very Slow	V. Sm
Meandrina sp.	5 - 30	W	MP - B	?	?	?	SM	?	Very Slow	Sm
Goreaugyra memorialis	> 30	W	?	_	_	_	CO	_	_	_
Colpophyllia natans	1 - 25	S	H - S	1	1-2	SU-FA	BO-MA-CR	0.3 - 1.1	Slow	Med - Lg
Colpophyllia amaranthus	5 - 20	S	H - S	1	1-2	SU-FA?	BO-MA-CR	0.3 - 1.1	Slow	Med - Lg
Colpophyllia breviserialis	5 - 20	S	H - S	1	1-2	SU-FA	BO-MA-CR	?	Slow	Med - Lg
Pseudodiploria clivosa	0 - 5	S	H - S	1	1-2	SU-FA	CR-SM	0.3 - 1.0	Slow	Med - Lg
Pseudodiploria strigosa	1 - 30	S	H - S	1	1-2	SU-FA	BO-MA-CR	0.33 - 1.0	Slow	Med - Lg
Diploria labyrinthiformis	3 - 25	S	H - S	1	1-2	SU-FA	BO-MA-CR	0.3 - 0.75	Slow	Med - Lg

Table 3: Traits

SPECIES NAME	Depth Range (m)	Life Hist-ory Strat-egy	REPRO-DUCTION pattern-mode	Yearly Gameto-genesis	Spawning/ brooding		Growth form	Growth rate (cm/year)	Growth	Mean size
					events	season				
Favia fragum	0 - 10	S	H - B	7-10	12	year-around	SM-CR	0.5	Slow	V. Sm
Manicina areolata	1 - 20	W	H - B	1	>1	SP-SU	SM	0.3 - 1.2	Slow	Sm
Manicina mayori	10 - 20	W	H - B	?	?	?	SM-CR	0.3 - 1.2	Slow	Sm
Isophyllia sinuosa	5 - 20	W	H - B	1	>1	SP-SU	SM-CR	0.5	Slow	Sm
Isophyllia rigida	5 - 20	W	H - B	1	>1	SU-FA	SM-CR	0.3	Very Slow	Sm
Isophyliia multiflora	10 - 20	W	?	?	?	?	SM-CR	?	Very Slow	Sm
Mycetophyllia ferox	5 - 25	W	H - B	2-4	>2	FA-WI	PL-CR	?	Slow	Sm - Med
Mycetophyllia aliciae	10 - 50	W	H - B	2-4	>2	WI-SP	PL-CR	?	Slow	Med - Lg
Mycetophyllia lamarckiana	10 - 30	W	H - B	2-4	>2	WI-SP	PL-CR	?	Slow	Sm - Med
Mycetophyllia danana	10 - 30	W	H - B	2-4	>2	WI-SP	PL-CR-SM	?	Slow	Sm - Med
Mycetophyllia resii	20 - 60	W	?	?	?		PL	?	Slow	Med - Lg
Scolymia cubensis	5 - 25	W	H - B	1	>1	SU-FA	SM-SP	?	Slow	V. Sm
Scolymia lacera	10 - 30	W	H - B	?	?	?	SM-SP	?	Very slow	V. Sm - Sm
Scolymia wellsi	15 - 35	W	H - B	1	>1	?	SM-SP	?	Very slow	V. Sm
Scolymia nsp.	> 20m	W	H - B	?	?	?	SM-SP	?	Very slow	V. Sm
Mussa angulosa	5 - 25	W	H - B	?	>1	?	BR-SM	?	Very slow	Med - Lg
Orbicella annularis	1 - 25	G	H - S	1	2-3	SU-FA	CO-BO-SM	0.4 - 1.4	Slow	Med - V. Lg
Orbicella faveolata	1 - 25	G	H - S	1	2-3	SU-FA	BO-MA-SM-CR	0.5 - 1.2	Slow	Med - V. Lg

Table 3: Traits

SPECIES NAME	Depth Range (m)	Life Hist-ory Strat-egy	REPRO-DUCTION pattern-mode	Yearly Gameto-genesis	Spawning/ brooding events	Spawning/ brooding season	Growth form	Growth rate (cm/year)	Growth	Mean size
Orbicella franksi	10 - 45	G	H - S	1	2-3	SU-FA	BO-MA-SM-CR	0.15 - 0.6	Slow	Med - V. Lg
Montastraea cavernosa	3 - 90	S	G - S	1	1	SU	BO-SM-CR	0.2 - 1.1	Slow	Med - Lg
Montastraea nsp.	10 - 30	S	G - S	1	1	SU	BO-SM-CR	0.2 - 0.7	Slow	Med - Lg
Porites astreoides	1 - 50	W	MP - B	2-7	>5	SP-SU-FA	CR-SM-PL	0.19 - 1.4	Slow	Med
Porites colonensis	5 - 20	W	? - B	?	?	?	PL-CR-SM	?	Slow	Sm
Porites porites	1 - 30	W	G - MP - B	2-5	>2	SP-SU-FA	BR	0.8 - 3.3	Fast	Med - V. Lg
Porites furcata	1 - 12	W	G - B	2-5	>2	SP-SU-FA	BR	0.9 - 5.3	Fast	Med - V. Lg
Porites divaricata	0 - 15	W	G - B	?	?	SP-SU-FA	BR	?	Fast	Med - V. Lg
Porites nsp.	0 - 5	W		?	?	?	SM-CR	?	Slow	V. Sm - Sm
Madracis decactis	5 - 50	W	H - B	1	>1	SP-SU-FA	BR-SM	?	Slow	Sm - Med
Madracis formosa	15 - 30	W	H - B	1	>1	SP-SU-FA	BR	?	Slow	Sml - Lg
Madracis carmaby	> 30	W	H - B	1	>1	SP-SU-FA	BR	?	Slow	Sm - Med
Madracis pharensis f luciphogous	5 - 30	W	H - B	1	>1	SP-SU-FA	SM-CR	?	Very slow	Sm

Table 3: Traits

SPECIES NAME	Depth Range (m)	Life Hist-ory Strat-egy	REPRO-DUCTION pattern-mode	Yearly Gameto-genesis	Spawning/ brooding		Growth form	Growth rate (cm/year)	Growth	Mean size
					events	season				
Madracis pharensis f. luciphylla	10 - 50	W	H - B	1	>1	SP-SU-FA	CR-SM	?	Very Slow	Sm
Madracis senaria	10 - 30	W	H - B	1	>1	SP-SU-FA	CR-SM	?	Slow	Sm - Med
Madracis auretenra	1 - 30	W	H - B	1	>1	SP-SU-FA	BR	0.7 - 2.4	Fast	Med - V. Lg
Madracis asperula	30 - 150	W	?	?	?	?	BR	2.0	Fast	Sm
Madracis myriaster	30 - 150	W	?	?	?	?	BR	?	?	Sm
Oculina diffusa	2 - 25	W	G - S	?	?	?	BR-CR	1.2 - 2.2	Fast	Sm - Med
Oculina varicosa	5 - 20	W	G - S	?	?	SU-FA?	BR-CR	?	?	Sm - Med
Oculina valecienesi	5 - 20	W	G - S	?	?	?	BR	?	?	Sm
Oculina robusta	10 - 30	W	G - S	?	>1	?	BR-CR	?	?	Sm
Siderastraea siderea	1 - 50	S	G - S	1	1	SU	CR-BO-SM	0.2 - 0.9	Slow	Med - Lg
Siderastrea radians	0 - 5	W	G - B	2-5	>2	SP-SU-FA?	CR-SM	0.15 - 1.8	Slow	V. Sm - Sm
Siderastrea stellata	5 - 25	C	?	?	?	?	CR-SM	?	Slow	Sm
Cladocora arbuscula	3 - 20	C	H - S	1	1-2	SU-FA	BR	?	?	Sm - Med
Solenastrea bournoni	3 - 20	S	G - S	?	?	SU-FA	MA-BO	0.9	Slow	Med - Lg
Solenastrea hyades	10 - 25	S	? - B	?	?	SU-FA?	SM	0.2	Very Slow	Sm - Med
Tubastraea coccinea	3 - 25	W	H - B	?	>3	SP-SU-FA	CR	?	?	Sm
Tubastraea micranthus	10 - 40	W	? - B	?	?	?	CR	?	?	Med
Tubastraea aurea	5-30	W	H - B	?	?	?	CR	?	?	Sm
Millepora alcicornis	1 - 40	C	G - B	?	?	?	BR-CR	0.2-0.75	Slow	Med-V. Lg

Table 3: Traits

SPECIES NAME	Depth Range (m)	Life Hist-ory Strat-egy	REPRO-DUCTION pattern-mode	Yearly Gameto-genesis	Spawning/ brooding		Growth form	Growth rate (cm/year)	Growth	Mean size
					events	season				
Millepora complanata	2 - 40	C	G - B	?	?	?	PL-CR	0.3 - 0.8	Slow	Lg - V. Lg
Millepora striata	5 - 15	C	G - B	?	?	?	BR		Slow	Med-Lg
Millepora squarrosa	5 - 15	W	G - B	?	?	?	SM-CR	2.24	Fast	Sm - Med
Stylaster roseus	3 - 50	W	G - B	?	?	?	BR		Slow	Sm

Table 4: Disease Susceptibility

SPECIES NAME	BBD	WBD	WPX	WPD	CYBD	DSD	GAN	RBD	CCI *	IMS **	SCTLD ***	OTH	BLE	N	OVER-ALL	BCG ATRIB.
Stephanocoenia intersepta	**	*		***		**		*	*		**	*	***	9	**	3-4
Acropora cervicornis	**	***	**	*?			*		**			*	***	7	***	3-4
Acropora palmata	*	***	***	*?			*		**			*	***	8	***	2-3
Acropora prolifera		**	*?	*?					*			*	**	3	*	4
Acropora sp.	*	***		*?									**	2	**	4
Undaria tenuifolia	*			*					**			*	***	5	*	4-5
Undaria agaricites	**			**		*		*	**		*	*	***	8	**	3-4
Undaria humilis	*			**							*	*	***	5	*	5
Undaria purpurea	*			**									**	3	*	5
Undaria carinata	?			*									**	3	*	
Undaria crassa	?			?									**	3	*	
Undaria danae	*			**		*		*	*			*	***	7	**	4-5
Undaria pusilla				*				*					***	3	*	4-5
Agaricia fragilis	*			*					*			*	***	5	**	5
Agaricia fragilis (Bermuda)				**								*	**	3	*	5
Agaricia lamarcki	*			**				*	*			*	**	6	**	4
Agaricia grahamae				*								*	**	3	*	4-5
Agaricia undata				*								*	**	3	*	4-5

Table 4: Disease Susceptibility

SPECIES NAME	BBD	WBD	WPX	WPD	CYBD	DSD	GAN	RBD	CCI *	IMS **	SCTLD ***	OTH	BLE	N	OVER-ALL	BCG ATRIB.
Leptoseris cailleti				*									**	2	*	5
Helioceris cucullata	*			*					*			*	***	5	*	5
Dendrogyra cylindrus	**			***			*		*		**	**	***	7	***	1-2
Eusmilia fastigiata				**							**	*	**	4	**	4-5
Eusmilia fastigiata f. flagellata				*					*		***		**	3	**	4-5
Dichocoenia stokesii	*			***							***	*	*	5	**	4
Dichocoenia stellaris	*			*					*				*	3	**	5
Meandrina meandrites	**			***		*		*	*		***	*	**	8	**	4
Meandrina Jacksoni	**			***		*	*	*	*		***		**	8	*	4-5
Meandrina danae				*									*	2	*	5
Meandrina sp. (Bermuda)	*			***					*			*	**	5	*	5
Goreaugyra memorialis	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	
Colpophyllia natans	**			***	*	**		*	*			*	***	8	**	3
Colpophyllia amaranthus	**			***	*	**			*			*	**	7	**	4
Colpophyllia breviserialis	**			**		**						*	***	5	**	3-4
Pseudodiploria clivosa	***			**	*		**		*			*	**	7	*	3-4
Pseudodiploria strigosa	***			***	*		**		**			*	*	7	**	3-4

Table 4: Disease Susceptibility

SPECIES NAME	BBD	WBD	WPX	WPD	CYBD	DSD	GAN	RBD	CCI *	IMS **	SCTLD ***	OTH	BLE	N	OVER-ALL	BCG ATRIB.
Diploria labyrinthiformis	***			***	*	*	**		***			*	**	8	**	3-4
Favia fragum	*			***							*	*	***	5	*	5
Manicina areolata	*			*									**	3	*	5
Manicina mayori	–	–	–	–	–	–	–	–	–	–	–	–	*	1	?	
Montastraea cavernosa	**			**	*	*			*	**	***	*	*	9	*	4-5
Montastraea nsp.(Large polyps)	**			**		*				**	***	*	*	7	*	5
Isophyliia sinuosa	*			**									*	3	*	5
Isophyllia rigida	*			**									**	3	*	4-5
Isophyliia multiflora	–	–	–	?	–	–	–	–	–	–	–	–	*	1	*	4-5
Mycetophyllia ferox	**			***				*			**	*	*	6	**	4
Mycetophyllia aliciae				**								*	*	3	*	5
Mycetophyllia lamarckiana	*			**				*				*	*	5	*	5
Mycetophyllia danana				**								*	*	3	*	5
Mycetophyllia resii				?									*	1	*	5
Scolymia cubensis				*					*				*	3	*	5
Scolymia lacera				*									*	2	*	5
Scolymia wellsi				*									*	2	*	5
Scolymia nsp.													*	1	*	1-2
Mussa angulosa				*				*					**	3	*	1-2

Table 4: Disease Susceptibility

SPECIES NAME	BBD	WBD	WPX	WPD	CYBD	DSD	GAN	RBD	CCI *	IMS **	SCTLD ***	OTH	BLE	N	OVER-ALL	BCG ATRIB.
Orbicella annularis	***			***	***	***		*	**	*	***	*	***	10	***	1-2
Orbicella faveolata	***			***	***	**	*	*	*	**	***	*	***	11	***	1-2
Orbicella franksi	**			***	***	*	*		*	**	***	*	*	10	**	4
Porites astreoides				**			*			*		*	*	5	*	4-5
Porites colonensis													?		?	
Porites porites	*			*					*			*	***	5	**	2-3
Porites furcata				*					*				**	3	*	5
Porites divaricata				*									**	2	*	5
Porites nsp.	–	–	–	*	–	–	–	–	–	–	–	–		1	?	
Madracis decactis				**					*				*	3	*	5
Madracis formosa				*									*	2	*	5
Madracis carmaby				*										1	*	5
Madracis pharensis f luciphogous				*									*	2	*	5
Madracis pharensis f. luciphylla				*										1	*	
Madracis senaria				**								*	*	3	*	5
Madracis auretenra				**					*			*	**	4	*	5
Madracis asperula	–	–	–	–	–	–	–	–	–	–	–	–	?	?	?	
Madracis myriaster	–	–	–	–	–	–	–	–	–	–	–	–	?	?	?	
Oculina diffusa				**									**	2	*	5
Oculina varicosa													**	1	*	5

Table 4: Disease Susceptibility

SPECIES NAME	BBD	WBD	WPX	WPD	CYBD	DSD	GAN	RBD	CCI *	IMS **	SCTLD ***	OTH	BLE	N	OVER-ALL	BCG ATRIB.
Oculina valecienesi				*									**	2	*	5
Oculina robusta													*	1	*	5
Siderastraea siderea	**			***		***					**	**	***	6	**	1-2
Siderastrea radians	*			***		**						*	**	5	*	4-5
Siderastrea stellata	*			**		**							*	4	*	5
Cladocora arbuscula				*									**	2	*	5
Solenastrea bournoni				**		***					***		**	4	*	4-5
Solenastrea hyades													?	?	?	
Tubastraea coccinea				*										1	?	5
Tubastraea micranthus														?	?	?
Tubastraea aurea				*										1	?	?
Millepora alcicornis				***					*			*	***	4	*	1-2
Millepora complanata	*			***					*			*	***	4	*	3-4
Millepora striata													**	1	*	5
Millepora squarrosa				**								*	***	3	*	5
Stylaster roseus				**									**	2	*	5

Table 5: BCG Attributes and Pathogenic Diseases

SPECIES NAME	Sediment Susceptibility	BCG ATTRIBUTE	Bleaching Susceptibility	BCG ATTRIBUTE	Disease Susceptibility	BCG ATTRIBUTE	PATHOGENIC DISEASES
Stephanocoenia intersepta	****	5	****	5	**	2-3	WPD - DSD - RBD - CCI - OTH - SCTLD
Acropora cervicornis	**	2-3	**	3-4	***	3-4	WBD - BBD - WPX - RBD - GAN - CCI - OTH
Acropora sp.	**	2-3	**	3-4	**	2-3	WBD - BBD - RBD - CCI - OTH
Acropora palmata	***	3-4	***	4-5	***	4-5	WBD - WPX - CCI - GAN - OTH
Acropora prolifera	**	2-3	**	3	**	2	WBD - CCI - OTH
Undaria tenuifolia	**	2-3	****	5	*	1-2	WPD - CCI
Undaria agaricites	****	5	****	4-5	**	2-3	WPD - RBD - DSD - CCI
Undaria humilis	****	5	****	4-5	**	2	WPD - CCI - RBD -DSD
Undaria purpurea	****	5	***	3-4	*	1	WPD - RBD
Undaria carinata	***	3-4	****	5	?		?
Undaria crassa	***	3-4	****	5	?		?
Undaria danae	**	2-3	***	4-5	**	2	WPD - BBD -RBD
Undaria pusilla	****	5	****	5	*	1	WPD
Agaricia fragilis	***	3-4	****	5	*	1	WPD - BBD - RBD
Agaricia fragilis	***	3-4	****	5	*	1	WPD - RBD
Agaricia lamarcki	****	5	****	5	**	2-3	WPD - RBD - OTH
Agaricia grahamae	****	5	***	4-5	*	1	WPD - OTH
Agaricia undata	****	5	***	4-5	*	1-2	WPD - OTH
Leptoseris cailleti	**	2-3	****	5	?		?
Helioceris cucullata	****	5	***	4-5	*	1	WPD - OTH
Dendrogyra cylindrus	*	1-2	**	3	***	4-5	WPD - CYBD - BBD - GAN - OTH - SCTLD
Eusmilia fastigiata	**	2-3	***	4-5	***	4	WPD - BBD - CCI - SCTL
Eusmilia fastigiata f. flagellata	**	2-3	***	4-5	***	4	WPD - CCI

Table 5: BCG Attributes and Pathogenic Diseases

SPECIES NAME	Sediment Susceptibility	BCG ATTRIBUTE	Bleaching Susceptibility	BCG ATTRIBUTE	Disease Susceptibility	BCG ATTRIBUTE	PATHOGENIC DISEASES
Dichocoenia stokesii	**	2-3	***	3-4	****	4-5	BBD - WPD - SCTLD
Dichocoenia stellaris	**	2-3	***	3-4	***	4	WPD - BBD
Meandrina meandrites	**	2-3	***	4	***	4	BBD - WPD - SCTLD
Meandrina Jacksoni	**	2-3	***	4	**	3	BBD - WPD - RBD- SCTLD
Meandrina danae	*	1-2	*	1-2	*	1	WPD
Meandrina sp.	**	3	**	3	**	2	WPD - BBD
Goreaugyra memorialis	_	_	_	_	_	_	_
Colpophyllia natans	***	3	***	3-4	****	4-5	BBD - WPD - DSD -RBD - GAN - CCI - SCTLD
Colpophyllia amaranthus	***	3	***	4	***	4	BBD - WPD - RBD- OTH - SCTLD
Colpophyllia breviserialis	***	3	***	3-4	****	4-5	BBD - RBD - WPD - DSD - CCI - SCTLD
Pseudodiploria clivosa	*	1-2	*	2	***	2-3	BBD-WPD-DSD-GAN-OTH-SCTLD
Pseudodiploria strigosa	**	2-3	*	2	***	2-3	BBD-WPD-CYBD-DSD-RBD-CCI-GAN-OTH-SCTLD
Diploria labyrinthiformis	**	2-3	***	3-4	****	4-5	BBD-WPD-CYBD-RBD-CCI-GAN-OTH-SCTLD
Favia fragum	*	1-2	***	3-4	*	1	BBD - WPD - DSD - OTH
Manicina areolata	*	1-2	**	3	*	1	WPD - OTH
Manicina mayori	**	2-3	**	3	?		?
Isophyllia sinuosa	**	2-3	*	1-2	*	1-2	BBD - WPD - OTH
Isophyllia rigida	***	3-4	*	1-2	*	1-2	BBD - WPD - OTH
Isophyliia multiflora	**	3	?	?	?		?
Mycetophyllia ferox	**	2-3	**	3	***	2-3	BBD - WPD - OTH - SCTLD
Mycetophyllia aliciae	**	2-3	*	1-2	**	2-3	WPD - OTH - SCTLD

Table 5: BCG Attributes and Pathogenic Diseases

SPECIES NAME	Sediment Susceptibility	BCG ATTRIBUTE	Bleaching Susceptibility	BCG ATTRIBUTE	Disease Susceptibility	BCG ATTRIBUTE	PATHOGENIC DISEASES
Mycetophyllia lamarckiana	***	3-4	*	1-2	**	2	WPD - RBD
Mycetophyllia danana	***	3-4	*	1-2	**	1-2	WPD
Mycetophyllia resii	**	1-2	*	1-2	*	1-2	WPD - OTH
Scolymia cubensis	*	1	**	1-2	*	1-2	WPD
Scolymia lacera	*	1	*	1	*	1	WPD
Scolymia wellsi	*	1	*	1-2	?		?
Scolymia nsp.	*	1	*	1-2	?		?
Mussa angulosa	**	1-2	*	1-2	**	1-2	WPD - OTH - SCTLD
Orbicella annularis	*	2	****	4-5	****	4-5	BBD-CYBD-WPD-DSD-RBD-CCI-GAN-OTH-SCTLD
Orbicella faveolata	**	3	****	4-5	****	4-5	BBD-CYBD-WPD-DSD-RBD-CCI-GAN-OTH-SCTDL-IMS
Orbicella franksi	**	3	***	4-5	***	4	BBD-CYBD-WPD-DSD-GAN-CCI-OTH-SCTLD-IMS
Montastraea cavernosa	*	1-2	**	3	**	2-3	BBD-WPD-DSD-CYBD-CCI-GAN-RBD-OTH-SCTLD-IMS
Montastraea nsp.	*	1-2	**	2	**	2-3	BBD - WPD - DSD - OTH - SCTLD - IMS
Porites astreoides	***	3-4	*	1-2	**	2-3	BBD - RBD - WPD - CCI - OTH
Porites colonensis	***	1-2	*	1-2	?		?
Porites porites	*	1-2	***	4-5	**	2-3	WPD - OTH
Porites furcata	*	1-2	**	3	*	1-2	WPD
Porites divaricata	*	1-2	**	3	*	1	WPD - OTH
Porites nsp.	***	4	**	3	*	1-2	WPD
Madracis decactis	**	3	*	1-2	*	1-2	WPD - OTH
Madracis formosa	**	3	*	1-2	*	1	WPD - OTH
Madracis carmaby	**	3	*	1	?		?

Table 5: BCG Attributes and Pathogenic Diseases

SPECIES NAME	Sediment Susceptibility	BCG ATTRIBUTE	Bleaching Susceptibility	BCG ATTRIBUTE	Disease Susceptibility	BCG ATTRIBUTE	PATHOGENIC DISEASES
Madracis pharensis f luciphogous	***	4	*	1-2	*	1	WPD-OTH
Madracis pharensis f. luciphylla	***	4	*	1	?		?
Madracis senaria	***	4-5	*	1-2	*	1-2	WPD - GAN
Madracis auretenra	*	1-2	**	2-3	**	1-2	WPD - OTH
Madracis asperula	?		*	1	?	?	?
Madracis myriaster	?		*	1	?	?	?
Oculina diffusa	*	1	**	3	*	1	WPD - OTH
Oculina varicosa	*	1	**	3	?		?
Oculina valecienesi	*	1	***	3-4	?		?
Oculina robusta	*	1	***	3-4	?		?
Siderastraea siderea	**	1-2	***	3-4	***	4	BBD - DSD - WPD -RBD - CCI - OTH - SCTLD
Siderastrea radians	*	1	**	3	*	1-2	BBD - DSD - WPD
Siderastrea stellata	*	1-2	**	2-3	*	1	WPD - GAN
Cladocora arbuscula	*	1	**	3	*	1	WPD
Solenastrea bournoni	**	2-3	**	3	**	2	BBD - WPD - DSD - OTH - SCTLD
Solenastrea hyades	**	1-2	?	?	?	?	?
Tubastraea coccinea	****	5	_	_	*	1	WPD
Tubastraea micranthus	***	4-5	_	_	?	1	?
Tubastraea aurea	****	5	_	_	*	1	WPD - OTH
Millepora alcicornis	**	2-3	****	5	**	2	WPD - OTH - GAN
Millepora complanata	**	2-3	****	5	**	3-4	BBD - WPD - OTH
Millepora striata	***	4-5	***	4-5	?		?
Millepora squarrosa	***	4-5	****	5	?		?
Stylaster roseus	*	1-2	***	4-5	?		?

Table 6: Distribution and Description

SPECIES NAME	GEOGRAPHIC DISTRIBUTION	OBSERVATIONS AND COMMENTS
Stephanocoenia intersepta	Wider Caribbean	Common but not highly abundant in northern Caribbean. Abundant in western and southern Caribbean. Small to medium sized colonies with smooth surface, deep, poligonal calices and tan to greenish coloration.
Acropora cervicornis	Wider Caribbean except Bermuda	Eadangered species (ESA-IUCN). Two conspicuous morphologies in the Caribbean, this one has thin, long branches, frequent lateral branching and fast growth. Good recovery reported for many localities but still impacted by WBD outbreaks, high predation rates by fireworms (*H. carunculata*) and snails (*C. abbreviata. C. caribbaea),* algae overgrowth and damselfish are major problems.
Acropora sp.	Central and southern Caribbean	Needs taxonomic verification. This thick growth form has been observed growing side by side with the thin, commom *A. cervicornis*. Common in the southern Caribbean
Acropora palmata	Wider Caribbean except Bermuda	Endangered species (ESA-IUCN). Recovering is been slow in most localities. Still affected by WBD-like signs, algae overgorwth and damselfishand fireworm predation
Acropora prolifera	Wider Caribbean except Bermuda	Hybrid taxon between *A. cervicornis* and *A. palmata*. Mophology depends on which parental species donated the egg or sperm. Dense, finger-like, short branches form compact colonies that seem more resistant to WBD-like infections and damselfish colonization.
Undaria tenuifolia	Central and Western Caribbean	One of 3 bifacial agaricids. Thin corallum forn large wide and vertical colonies that can monopolize extensive habitats. Most common in north-central, south central and western Caribbean.
Undaria agaricites	Wider Caribbean except Bermuda	Submassive, crustose colonies.
Undaria humilis	Wider Caribbean except Bermuda	Small, massive-crustose colonies with reticulated high ridges and closed valleys with few calices
Undaria purpurea	Wider Caribbean except Bermuda	Reticulated ridges and closed valleys with few mouths inside.
Undaria carinata	Western Caribbean	Needs taxonomic varification. Posibly endemic to south central America
Undaria crassa	Western Caribbean	Needs taxonomic verification. Posibly endemic to south central America and Colombia

Table 6: Distribution and Description

SPECIES NAME	GEOGRAPHIC DISTRIBUTION	OBSERVATIONS AND COMMENTS
Undaria danae	Wider Caribbean except Bermuda	Thick bifacial blades with a foliose/plate base. Abundant in well exposed, deeper (12-25m) habitats.
Undaria pusilla	Western and Central Caribbean	Small, cryptic thin crusts with low ridges, short valleys and small calices. In shallow, well exposed habitats
Agaricia fragilis	Wider Caribbean except Bermuda	Small, dark-colored, round/oval plates with low ridges and long valleys with tiny calices.
Agaricia fragilis	Bermuda	Posible endemic species for Bermuda - different from *A. fragili*s in the Caribbean
Agaricia lamarcki	Wider Caribbean except Bermuda	Wide depth distribution, from 10 to 70 m depth
Agaricia grahamae	Wider Caribbean except Bermuda	Needs genetic verification - mesophotic deep coral
Agaricia undata	Wider Caribbean except Bermuda	Mesophotic species
Leptoseris cailleti	Wider Caribbean ???	Mesophotic to deep water coral
Helioceris cucullata	Wider Caribbean except Bermuda	A slightly different form called "*formae contracta*" has been described for some localities.
Dendrogyra cylindrus	Wider Caribbean except Panama and Bermuda	Threatened species.
Eusmilia fastigiata	Wider Caribbean except Bermuda	Typical faceoloid (Flower-like) colony, with separate, large calices calices and intratentacular division. Tan to yellow.
Eusmilia fastigiata f. flagellata	Caribbean	Meandroid, ellongated calices with several mouths that could be the early stages of intratentacular budding.
Dichocoenia stokesii	Wider Caribbean	Small to mediun sized (40cm) colonies with elongated calices and wide coenosteum. Typically orange-yellow or pale.
Dichocoenia stellaris	Wider Caribbean	Needs Taxonomic verification

Table 6: Distribution and Description

SPECIES NAME	GEOGRAPHIC DISTRIBUTION	OBSERVATIONS AND COMMENTS
Meandrina meandrites	Wider Caribbean except Bermuda	Thick septa and deep narrow valleys - Possibly not in Bermuda since the taxon there is diferent
Meandrina Jacksoni	Wider Caribbean except Bermuda	Recently described. Crustose/plate coralla, wide, pale valleys and low ridges
Meandrina danae	Wider Caribbean except Bermuda	Confused with *M. brasiliensis* which is endemic to Brazil
Meandrina sp.	Bermuda	This is probably a different, endemic species. Needs taxonomic verification
Goreaugyra memorialis	Only specimen found in the Bahamas	The only existing specimen is a short column with wide ambulacra and deep valleys on the side. The top morphology and calical structure are similar to *M. meandrites*. Specimen collected in deep waters in the Bahamas.
Colpophyllia natans	Wider Caribbean except Bermuda	Large boulder and crustose coralla
Colpophyllia amaranthus	Wider Caribbean except Bermuda ??	Probably restricted distribution. Common in north and southern Caribbean
Colpophyllia breviserialis	Wider Caribbean except Bermuda	Needs taxonomic verification (genetic). Low abundances and mixed morphology colonies with *C.natans* type common.
Pseudodiploria clivosa	Wider Caribbean	Shallow water mostly. Crustose to submassive colonies with irregular, bumpy surface
Pseudodiploria strigosa	Wider Caribbean	Crustose, platy and hemispherical meandroid colonies. Narrow ridges and eep valleys, no ambulacra.
Diploria labyrinthiformis	Wider Caribbean	Mostly round hemispherical colonies with wide ridges and ambulacra, and deep narrow valleys. Mostly orange-yellow
Favia fragum	Wider Caribbean	Round small corallum, abundant in shallow, protected (back reef) habitats
Manicina areolata	Wider Caribbean except Bermuda	Lives on sediment areas, like Thallasia beds.
Manicina mayori	??	Needs genetic and more ecological data
Isophyllia sinuosa	Wider Caribbean	These two are considered to belong to a single genus*: Isophyllastrea*
Isophyllia rigida	Wider Caribbean except Bermuda	These two are considered to belong to a single genus*: Isophyllastrea*

Table 6: Distribution and Description

SPECIES NAME	GEOGRAPHIC DISTRIBUTION	OBSERVATIONS AND COMMENTS
Isophyliia multiflora	Caribbean ??	Rare growth form with closed valleys. Needs taxonomic verification.
Mycetophyllia ferox	Wider Caribbean except Bermuda	Mediun sizes plates with narrow ridges acros whole colony, opne and closed valleys
Mycetophyllia aliciae	Wider Caribbean except Bermuda	Shallow, wide valleys, discontinuous ridges.
Mycetophyllia lamarckiana	Wider Caribbean except Bermuda	Deep and wide valleys, discontinuous, wide ridges
Mycetophyllia danana	Wider Caribbean	Deep and narrow valleys, continuous, wide ridges
Mycetophyllia resii	Wider Caribbean	Deep water species. Flat plates with no ridges across corallum.
Scolymia cubensis	Wider Caribbean	Small, single polyps in criptic areas of the reef. Multicolored.
Scolymia lacera	Wider Caribbean except Bermuda	Largest, singke polyp species in the Caribbean. Fleshy polyps up to 15-20 cm in diameter. Multiple coloration
Scolymia wellsi	Eastern Caribbean ??	Endemic to Brazil, presence in Caribbean needs Taxonomic verification
Scolymia nsp.	North Gulf of Mexico ??	Under study. Only observed in the Flower Gardens
Mussa angulosa	Wider Caribbean except Bermuda	Large polyps growing in a faceoloid growth form. Intratentacular division. Multicolored.
Orbicella annularis	Wider Caribbean except Bermuda	Recently reclassified into a different family. Threatened species (ESA-IUCN)
Orbicella faveolata	Wider Caribbean	Recently reclassified into a different family. Threatened species (ESA-IUCN))
Orbicella franksi	Wider Caribbean	Recently reclassified into a different family. Threatened species (ESA-IUCN)
Montastraea cavernosa	Wider Caribbean	Wide depth distibution.
Montastraea nsp.	Wider Caribbean except Bermuda	Under study. Morphometric, ecological and behavioral data indicates is different from small polyped *M. cavernosa*
Porites astreoides	Wider Caribbean	Wide depth distribution and colormorphs

Table 6: Distribution and Description

SPECIES NAME	GEOGRAPHIC DISTRIBUTION	OBSERVATIONS AND COMMENTS
Porites colonensis	Endemic to south-west Caribbean	Submassive, and thin plates. Dark brown or olive green with bright calices
Porites porites	Wider Caribbean	Thick, long or short branches
Porites furcata	Wider Caribbean except Bermuda	Thinner branches than *P. porite*s, dichotomous and long. Back lagoonal habitats and slopes.
Porites divaricata	Wider Caribbean except Bermuda	Short, thin, dichotomous branches, back and lagoonal reefs and seagrass habtats and sometimes found in front reef slopes. Yellow tan and grey colorations.
Porites nsp.	Central Caribbean	Common small crustose, smooth, bluish species found in shalow, exposed habitats of central Caribbean. *P. branneri* is endemic to Brazil. Under study.
Madracis decactis	Wider Caribbean	Short, green-gray nobby branches. Wide depth distribution
Madracis formosa	Wider Caribbean	Long, chocolate brown sometimes flattened branches, yellow calices. Dee pslopes and sandy areas
Madracis carmaby	Curacao and southern Caribbean only??	Short, brown or olive green rounded branches, smaller colonies than *M. formosa*
Madracis pharensis f luciphogous	Wider Caribbean except Bermuda	Taxon without zooxanthellae
Madracis pharensis f. luciphylla	Wider Caribbean except Bermuda	Needs taxonomic verification. Taxon with zooxanthelae in deep, exposed habitats.
Madracis senaria	Wider Caribbean except Bermuda	Semi criptic, submassive colonies with five exerted primary septa that are distinctive, diagnostic traits
Madracis auretenra	Wider Caribbean	Long, thing pale to yellow branches. Incorrectlky clasified as *M. mirabilis.*
Madracis asperula	Caribbean ??	Needs taxonomic verification. Deep reef and mesophotic coral comunities
Madracis myriaster	Caribbean ??	Deep reef and Mesophotic coral communities
Oculina diffusa	Wider Caribbean	Can form large thickets in protected habitats
Oculina varicosa	Wider Caribbean	Short, thick branches and small colonies.
Oculina valecienesi	Wider Caribbean except Bermuda	Restricted to the cnetral and southern Caribbean

Table 6: Distribution and Description

SPECIES NAME	GEOGRAPHIC DISTRIBUTION	OBSERVATIONS AND COMMENTS
Oculina robusta	Florida - Eastern coast US	More common in temperated environments - azooxanthellated
Siderastraea siderea	Wider Caribbean	Wide depth and habitat distribution
Siderastrea radians	Wider Caribbean	Small, crustose and round colonies in shallow water habitats
Siderastrea stellata	Endemic to Brasil ???	Needs Taxonomic verification
Cladocora arbuscula	Wider Caribbean except Bermuda	Short branching polyps, associated with soft bottoms and seagrasses
Solenastrea bournoni	Wider Caribbean except Bermuda	Round, hemispherical medium sized colonies. Brownish to green coloration.
Solenastrea hyades	Wider Caribbean except Bermuda	limited distribution, murky environments, small corallum
Tubastraea coccinea	Wider Caribbean except Panama and Bermuda	Uncertain taxonomic status. Caribbean taxon (*T. aurea*) Genetic verification needed to separate from *T. coccinea*
Tubastraea micranthus	Northern Gulf of Mexico - Hispaniola	Invasive species, mostly in northern Gulf of Mexico, Dominican Republic
Tubastraea aurea	Wider Caribbean except Bermuda	Uncertain taxonomi status, being called T. coccinea but evidence of genetic, morphometric differences exist (Weil unpub)
Millepora alcicornis	Wider Caribbean	Hydrozoan
Millepora complanata	Wider Caribbean	Hydrozoan
Millepora striata	Western Caribbean Only ??	Hydrozoan, restricted distribution to the western Caribbean
Millepora squarrosa	Central and outhern Caribbean	Hydrozoan
Stylaster roseus	Wider Caribbean except Bermuda	Hydrozoan

Appendix S – Generalized Stressor Gradient

Leah Oliver

The BCG expert panel discussed the concept of a generalized stressor axis (GSA) and concluded that three stressors should be considered for coral reefs based on a broad body of supporting literature and their cumulative knowledge that deleterious impacts on reef health and biota are associated with increases in: (1) land-based sources of pollution, (2) fishing pressure, and (3) global climate change-associated thermal anomalies. A summary of their recommendations is shown in Appendix Q).

Here, additional information about these stressors is presented including some of the research efforts that demonstrate their connections with reef health, caveats associated with applying each to predict reef condition decline, and data needs to further develop a coral reef BCG for maximum regulatory effectiveness.

Land-based sources of pollution.

EPA began stressor axis research by testing distance to a source of human disturbance as a proxy for exposure of coral reefs to anthropogenic impacts on the island of St. Croix (Fisher et al. 2008). For this study, each disturbance area had numerous sources of human disturbance such as high-traffic shipping, intense near-coastal urban development, sewage treatment and commercial/industrial activities. Surveys of stony coral condition and extent showed increased impairment associated with greater levels of anthropogenic disturbance, diminishing with greater distance from the disturbance, thus establishing a key relationship between anthropogenic stress and the condition of reef-building corals and indirectly, the condition of reef-dependent fauna. This study established responsiveness of stony coral indicators (Fisher et al. 2007) to human disturbance, consistent with other research in the Caribbean and around the world relating reef condition to environmental gradients (Smith et al. 2008; Jupiter et al. 2008; Golbuu et al. 2008; Maina et al. 2011). A clear and intuitive connection between distance from robust centers of multiple disturbances and coral condition was demonstrated that laid the groundwork for further research on specific stressors.

Subsequent efforts applied a Landscape Development Intensity (LDI) index which demonstrated a link between land-based human activity and coral reefs in USVI (Oliver et al. 2011; Oliver et al. 2018). The LDI is an integrated measure of the intensity of human activities in a landscape or watershed, estimated by calculating the input of nonrenewable energy to different land use parcels. To calculate the LDI index, land use / land cover (LULC) raster data available from the National Land Cover Dataset (Homer et al. 2015) is reclassified from LULC categories to corresponding LDI coefficients (Brown and Vivas 2005). Coefficients represent energy inputs associated with activities specific to land uses, for e.g. agricultural lands cultivated for row crops are usually tilled, treated with fertilizer and pesticides, and harvested using petroleum-fueled tractors, hydraulic sprayers, or airplanes. These energy inputs are reflected in a higher LDI coefficient than that for lands cultivated for pasture/hay crops, which typically require less mechanized vehicles and reduced energy inputs. The premise that ecological communities are affected by cumulative human impacts in the surrounding watershed as quantified by the LDI index was shown for wetlands (Brown and Vivas 2005). The LDI index was demonstrated to be an effective landscape indicator of human impact for St. Croix and St. Thomas corals and was included in a multi-stressor conceptual model developed for Puerto Rico (**Figure 1a**).

The LDI index incorporates numerous human impacts that are negatively associated with coral reef condition including land conversion for industry, urban development and agriculture. These activities tend to increase sediment, nutrient and chemical pollution reaching coral reefs. Potential application of the LDI in a regulatory context supported by a BCG framework could involve setting LDI threshold values commensurate with sustainable reef condition for coastal watersheds, and if biological condition of coral reefs falls below target levels, land use change analysis could be conducted to determine possible origins of stressors to corals (EPA 2016, Ch 5). Analysis of land use / land cover data layers periodically released on a national scale (Homer et al. 2015) can reveal changes in land use that result in higher LDI index. Potential impacts to coastal resources from intensification of human impact or from proposed mitigation efforts can be modeled by reclassifying land use data to hypothetical scenarios and examining corresponding LDI index values. The LDI index can be calculated for different sized basins to suit the spatial distribution of coral reefs or other coastal resources of concern, and / or adapted for application to land areas of special concern where near-coastal development threatens valuable coastal resources. A limitation of LDI in its integrative nature is that specific stressors are not obvious without some understanding of the technical details behind the index. If incorporated in communications such as stakeholder engagement in developing coral reef management approaches, some care towards explaining the LDI or any multi-stressor index should be taken.

Sedimentation is an important stressor on coral reef ecosystems and was included in narrative rule development for the coral reef BCG (Bradley et al. 2014). Near-coastal coral reefs evolved in shallow water where sediment naturally enters the ocean and have mechanisms such as mucus production that vary by species (see Appendix M) that can clear sediment to some extent. Sediment can smother corals, inhibit photosynthesis by reducing available light, limit growth rates and disrupt interactions with reef-dependent fish through loss of structural habitat (see Appendix Q for examples of sediment effects on corals and fish).

Deleterious impacts to coral ecosystems from sediment exposure often stem from increased sediment loading to coastal environments from land clearing for development and loss of riparian vegetation that slows the pace of runoff. Sediment resuspension also contributes to increased exposure and is exacerbated by human activity in coastal ports where high traffic from cruise ships, industrial shipping and recreational boating can result in repeat exposure to sediment present in shallow coral habitats (Kisabeth et al. 2014). A benthic sediment threat (BST) model developed by WRI and NOAA's (2006) "Summit to Sea" analysis was applied in an EPA reef survey conducted in 2010 on Puerto Rico's south shore. The BST was derived from estimated sediment production on land using soil type and relative erodibility, precipitation data and slope, coupled with an inverse distance weighting function to simulate sediment threat to coastal habitats expected to disseminate further from shore without accounting for current or wind effects. The Shannon-Weiner diversity index for stony coral communities at 76 sites was inversely correlated with BST (Oliver LM, unpublished data) and principal components analysis suggested inverse relationships between BST and stony coral indicators (Oliver et al. 2013). The BST was included in multivariate analysis of fish BCG metrics and results suggested that increased BST was associated with reduced BCG level, supporting application of this type of sediment model in a BCG context (Bradley et al. 2020).

Elevated levels of nutrients including nitrogen and phosphorus from both non-point and point sources are established reef stressors (Fabricius 2005) that should be incorporated as a comprehensive GSA is built. These dissolved contaminants are highly variable and characterizing relevant exposure requires sufficient temporal sampling to capture long-term trends and at a spatial scale relevant to reef management decisions. The Australian government's approach to integrated management of the Great Barrier Reef provides such an example in the Marine Monitoring Program for Inshore Water Quality which monitors total suspended solids, chlorophyll a, phosphorus, nitrogen and pesticides on a regular basis and during high-flow events. Calculations of stressor contributions from catchment runoff and river transport are components of the coral reef adaptive management plan.

Water quality monitoring under the U.S. Clean Water Act provides limited data to inform a GSA. For example, in 2018, 104 Puerto Rico coastal sites were sampled under auspices of the Clean Water Act for potential exceedances of chemical and nutrient criteria linked to designated uses in waterbodies. Monitoring of waterbodies for potential impairments under the CWA is done every other year, a periodicity too infrequent to inform a reef BCG stressor gradient, and site locations are not related to reef locations. Even a robust water quality monitoring program cannot protect coral reefs without species specific dose-response relationships to facilitate chemical or nutrient criteria setting to ensure sustainability of reefs and ecosystem services they provide to humans.

Improving estimates of the influence of land-based stressors on coral reefs requires better understanding of transport mechanisms that deliver sediment, nutrient and chemical pollution to reef habitats. Relationships described here between high-LDI watersheds and reefs adjacent to those watersheds employed simple assumptions such as reefs located adjacent to a watershed are affected by that watershed, large-scale ocean currents should be incorporated when possible, and effects are generally dissipated with greater distance from shore (Oliver et al. 2011, 2018). In contrast with stream ecosystems where the BCG has been successfully applied (Hausmann et al. 2016; Gerritsen et al. 2017), quantifying a generalized stressor axis for coastal ecosystems that accounts for all relevant stressors presents numerous challenges. Stream ecosystems have one-directional transport of pollutants with consistent downstream dilution, an assumption that does not apply to coastal systems. Upon entering the coastal environment, nonpoint runoff and river borne contaminants generally dissipate with increasing distance from shore-based sources, but quantifying stressor delivery to reefs requires an understanding of hydrological influences, runoff dynamics, variable ocean currents, bathymetry, and wind. Accounting for near-shore ocean current patterns, wind, and bathymetry is needed to enhance understanding of the fate and transport of pollutants in the near-coastal environment. For Caribbean reefs, the finest-scale ocean current data is available via high-frequency radar for Puerto Rico's west coast. An array of ocean current- and wind-sensing buoys provides general current patterns around the island, operated by the Caribbean Coastal Ocean Observing System (CARICOOS), a regional component of the U.S. Ocean Observing System. This system is undergoing improvements that may be applicable to pollutant transport modeling, such as recent improvements that build from the CARICOOS system to forecast a 3-day timespan of ocean currents, water levels, temperature and salinity (Solano et al. 2018). Expanding high-frequency radar and/or buoy networks to cover near-coastal areas in all Caribbean islands would be helpful in predicting impacts of land-based stressors on coral reefs at a scale that is compatible with reef distribution around these islands.

Numerous approaches are available that could apply as the GSA axis for Caribbean corals is developed. Sediment and nutrient discharge from Puerto Rico rivers were analyzed by Warne et al. (2005) using stream gage and water quality data in an island-wide characterization of runoff and stressor delivery. Distinct regions of Puerto Rico were described that highlight the importance of rainfall and watershed characteristics such as topography in determining sediment delivery. Remote sensing and aerial imagery may be integrated with water quality analysis to estimate catchment production of land-based stressors such as sediment, transported to Great Barrier Reef coral habitats via river plumes (Devlin and Schaffelke 2009). Watershed modeling of sediment yield using the Soil and Water Assessment Tool (SWAT) for the Río Grande de Añasco in west Puerto Rico was coupled with remote sensing and aerial photography to better understand the extent and transport of sediment plumes in this area (Ramos-Scharrón and Gilbes 2014). Tools such as remote sensing will continue to improve as will methods to map the extent and health of reef systems.

Larger-scale sediment plume modeling to predict potential delivery to Indonesian reefs offers an approach to coupling watershed sediment production with an ocean transport model that accounts for current dynamics and particle settling (Rude et al. 2015). Watershed sediment production was coupled with an ocean transport model that included a sediment settling component, and due to the large scale of interest, ocean current data from globally available

HYCOM (Global Hybrid Coordinate Ocean Model) data at approximately 8.3 km resolution could be applied.

Models such as the BST could be improved by validating with field data to develop realistic functions for offshore sediment transport. Sediment cores collected on the south coast of Puerto Rico were evaluated using radionuclide and percent carbonate analysis to estimate trends in sediment accumulation and extent of offshore transport of terrigenous sediment (Ryan et al. 2008). Cores represent years of sediment deposition and provide a useful historical surrogate. Sediment trap studies also provide an indication of shore to shelf sediment transport (Hernández et al 2009) and illustrate the importance of sediment resuspension as a stressor to corals. These examples focused on reef areas off the coast of La Parguera and could contribute to developing sediment decay functions for analogous areas, where there are no major rivers and rainfall is generally low.

Fishing Pressure.

Over-fishing has dramatically altered the composition of biological communities on Caribbean coral reefs and seagrass beds. Large herbivores and carnivores such as turtles, groupers and sharks that were historically abundant are now ecologically extinct (i.e., populations are so greatly reduced relative to past levels that they no longer fulfill former ecological/functional role). The reduction of these species has resulted in "trophic level dysfunction" (Steneck et al. 2004), with food chains now dominated by small fishes and invertebrates (Hay 1984, 1991; Knowlton et al. 1990; Jackson 1997).

In addition to direct effects on fish populations and trophic stability, fishing pressure indirectly disrupts coral reef ecosystems through reduced herbivory which exacerbates other impacts on the health and ecological fitness of stony corals.

For Caribbean fisheries, spatial data that encompasses all types of fishing pressure is needed for optimal development of a BCG-based regulatory framework. For example, in his PhD thesis, Ruiz Valentín (2013) evaluated fishing pressure on the island of Puerto Rico based on i) total commercial fishery landings, ii) commercial fishing effort, iii) number of traps per fishing zone, and iv) recreational fishing, using the geographic location of marinas and boat ramp densities per square kilometer. Shivlani and Koeneke (2011) estimated commercial Puerto Rico fishing effort based on interviews with fishers (**Figure 1c**). Participants were asked to map fishing areas they used and the number of trips to each. Along with commercial fishing, recreational fishing data (López-Pérez et al. 2013) must be incorporated towards a complete accounting of fishing pressure on reef ecosystems, as summarized in a historical context for Puerto Rico by Appeldoorn et al. (2015).

Global climate change (GCC) Associated Thermal Anomalies.

Hermatypic corals form the essential structure of reef ecosystems in warm, shallow, oligotrophic waters and have evolved with low natural variability in physical parameters such as temperature, pH, alkalinity and calcium carbonate saturation state (Hoegh-Guldberg et al. 2007; Eakin et al. 2009). Growth of coral reefs depends upon the balance between symbiotic algae or "zooxanthellae" of genus *Symbiodinium* and coral tissues they inhabit, a relationship that is disrupted by minor deviations in temperature from geographically specific tolerance ranges (Coles et al. 1976). Coral "bleaching" or zooxanthellae loss occurs when the thermal tolerance limit of corals and their symbiotic algae is exceeded (Hoegh-Guldberg 1999). In addition to temperature, ocean acidification shifts equilibrium of the calcification process and affects corals' ability to build calcium carbonate skeletons (Kleypas et al. 2006).

Global-scale changes in climate that are associated with coral bleaching are not within the regulatory scope of Caribbean jurisdictions but their inclusion in a coral GSA is critical to capture all relevant stressors. Temperature stress may act synergistically with human impacts (Hoegh-Guldberg et al. 2007) that can be regulated by reducing coral resilience. Understanding thermal conditions at scales compatible with regulatory goals is an important component in decisions related to fishing regulations, near-coastal development and runoff control. Thermal history is among the most important factors influencing coral reef resilience and NOAA's Coral Reef Watch Program (CRW) uses satellite data to provide current and past reef environmental conditions to identify areas at risk for coral bleaching (Eakin et al. 2009, 2010; Muñiz-Castillo et al. 2019). Several thermal history metrics have been developed on a global scale that effectively predict likelihood of bleaching in real time, including degree heating weeks (DHW) which indicates the number of weeks that average ocean temperatures have been exceeded. Of particular interest for the coral reef BCG-GSA are experimental products that CRW has developed with support from the NOAA Coral Reef Conservation Program - thermal history metrics including SSTA for coral reef management at higher resolution (Muñiz-Castillo et al. 2019). SSTA represents positive or negative deviations from average monthly climatology, which is based on historical records of mean monthly night-time SST values (Liu 2014). Sea surface temperature anomalies (SSTA) are shown in **Figure 1b** as average from 2014-2016 at 5-km resolution for Puerto Rico.

Several issues require additional research to develop a GSA that incorporates synergistic effects of thermal stress with other stressors. For example, the frequency and duration of thermal anomalies associated with impaired coral resilience, and how these interact with land-based pollution from precipitation-related, pulsed events needs to be better understood. Species-specific responses to thermal stress must be incorporated (see Appendix M). Further development of CRW thermal history data products will provide information on frequency of events and historic patterns that can be analyzed with other stressors and related to reef condition (Hughes and Connell 1999). Incorporating the long recovery times of coral reefs and the overall ability of the system to recover (resilience) must also be considered.

The Stress Axis.

The x-axis of the BCG framework, the Generalized Stress Axis or GSA, conceptually describes the range of anthropogenic stress that may adversely affect aquatic biota in a particular area. It is a theoretical construct that seeks to represent the cumulative stress that may influence biological condition. A spatially explicit approach to stressor integration including land-based pollution, thermal anomalies, and fishing pressure was developed for Puerto Rico (**Figure 1d).** Land-based pollution was represented by the LDI, calculated for HUC12 watersheds to capture variation in the intensity of human activity on a scale proportional to coastal reefs (**Figure 2**). The LDI was mapped with a hypothetical maximum offshore buffer distance of 10 km and an assumption of diminished effects further from shore including a 50% reduction from 2-7 km offshore, and a 70% reduction from 7-10 km offshore. Thermal anomaly data as the SSTA from NOAA's Coral Reef Watch Program (CRW) represented deviations from average climatology for 2014 – 2016 and has the smallest resolution of thermal history data products of 5 km. Commercial fishing intensity data at a resolution of 3.3 km was provided by Manoj Shivlani, derived from engagement with fishers who were asked to estimate a maximum number of trips to each grid cell employing gear types nets, lines, traps and dive gears (spear guns and hand gathering).

Mapping multiple stressors for Puerto Rico coral reefs underscored data needs described above for each stressor and demonstrated technical aspects of combining data types into an integrated index. For example, although the LDI is shown with an island-wide influence buffer that indicates reduced impact of land-based stressors further from shore, these distances are only hypothetical and do not incorporate ocean currents, wind or bathymetry (**Figure 1a**). NOAA sea surface temperature anomaly (SSTA) data as shown in **Figure 1b** included all deviations from average whether high or low and might be tailored for specific exposure periods such as summer months when positive SSTA values are often associated with coral bleaching on larger scales. Commercial fishing data was spatially analyzed from direct recounts of fishers (**Figure 1c**), but ideally recreational fishing would be represented as well as more recent commercial fishing data. By re-scaling these stressor estimates as 0-3 and adding them, the resulting integrated stressor map (**Figure 1d**) illustrates where some Puerto Rico reefs could experience stress from one of these 3 stressors but not from all. Coral reefs off Puerto Rico’s south shore for 2014-2016 experienced relatively less thermal stress compared to the north but are adjacent to intense land development and/or fishing. The ability to examine single stressors that comprise a comprehensive GSA as well as the cumulative stressor gradient support a regulatory approach that can compare scenarios on a local scale such as infrastructure investments to control runoff in a context that includes other factors where such projects are most likely to achieve goals. Integrating stressors should incorporate the best available understanding of interactions whether additive, synergistic or antagonistic into weighting factors for each.

Typically, states have defined a stress gradient using single stressors or a combination of known, measurable stress gradients that in reality represent a portion of the stressors impacting a water body. The conceptual GSA provides a framework to assist in developing the most comprehensive stress gradient as possible to relate diminished levels of biological condition to increased stressors. A well-defined, quantitative GSA and the underlying data used to develop it may serve as a nexus between biological and causal assessments, thereby linking management goals and selection of management actions for protection or restoration. Systematic testing of technical approaches to define and apply a GSA to BCG development has not been conducted. Opportunities in the future may include piloting methods for application of national, regional, or basin-scale databases and methods to support efforts to quantify a GSA for a specific geographic region and water body type.

Here, the BCG is applied to coral reef ecosystems of Caribbean territorial islands. This serves as an exemplar to apply the approach to other coastal and marine resources that are at risk from a multitude of stressors. Seagrass and mangrove habitats occur in shallow waters close to the coastline, where risk of exposure from anthropogenic activities on land are highest (**Figure 2**). Decision-makers and stakeholders of any jurisdiction can come together and define relationships between gradients of biotic condition and gradients of anthropogenic stress that incorporate their best collective knowledge and strive to meet common conservation goals. Once strata of biological condition and relative stressor impacts are established, the BCG provides a flexible framework for continual improvement to solidify causal relationships and incorporate the best available data for stressors and resource condition as it becomes available. Jurisdictions can set resource management goals tied to BCG biological condition linked to their needs that account for societal, economic and ecosystem service values in currencies. The BCG framework is a systematic, effective process that facilitates multiple stakeholder involvement and is transferrable to coastal and marine resources that must be protected to preserve ecological integrity and sustainable provision of ecosystem services.

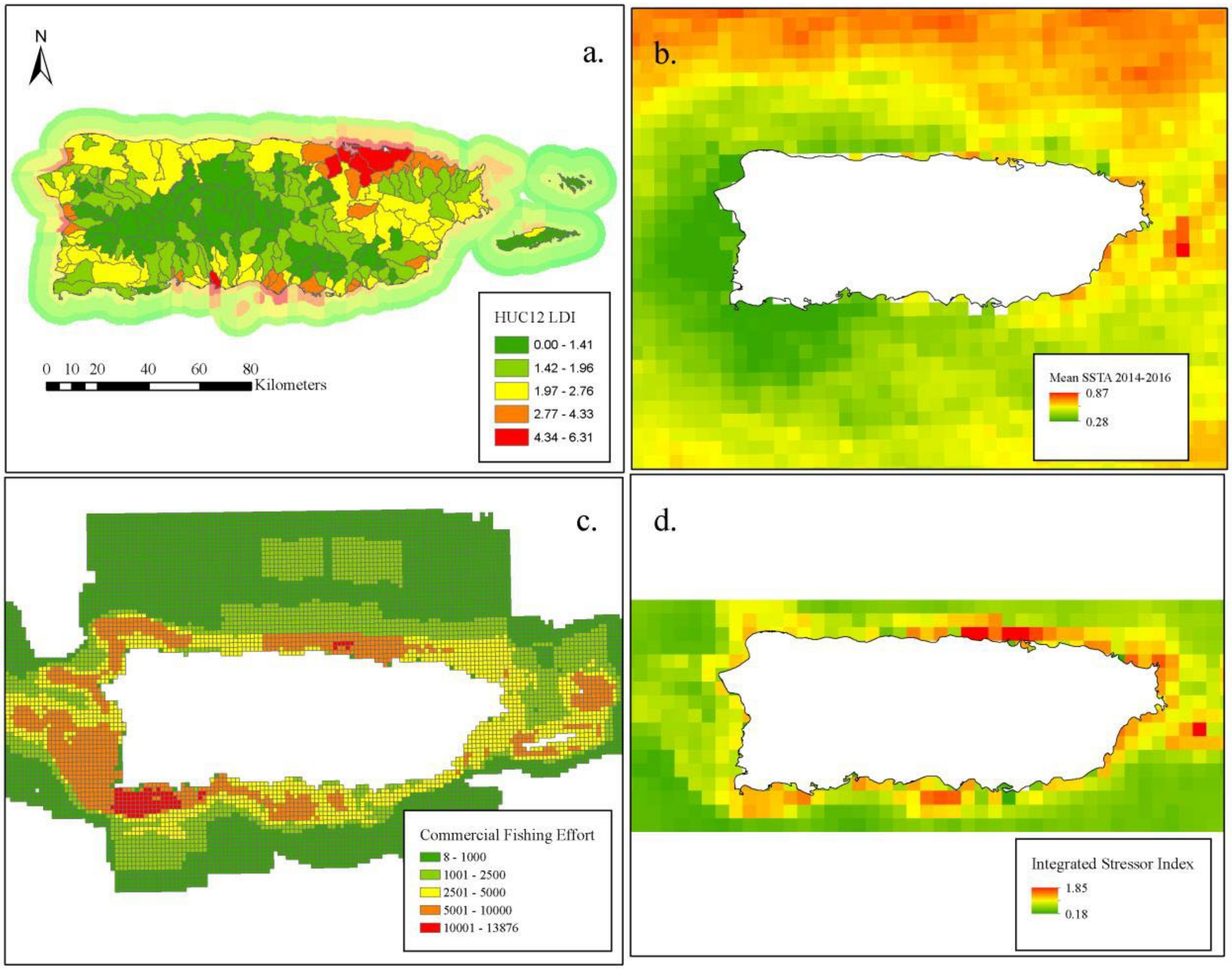


Figure S1. (from Oliver et al. 2016) a. Hydrologic Unit Code (HUC12) watersheds of Puerto Rico and associated LDI values. Offshore buffer zones show attenuated LDI value with increased distance from shore. b. NOAA Sea Surface Temperature Anomaly (SSTA), mean of monthly composites from 2014-2016. c. Total fishing effort modeled as maximum possible trips to each grid cell (Shivlani and Koeneke 2011). d. Integrated stressor index was calculated by re-scaling all three stressors (0-1) and summing for a maximum possible value of 3.

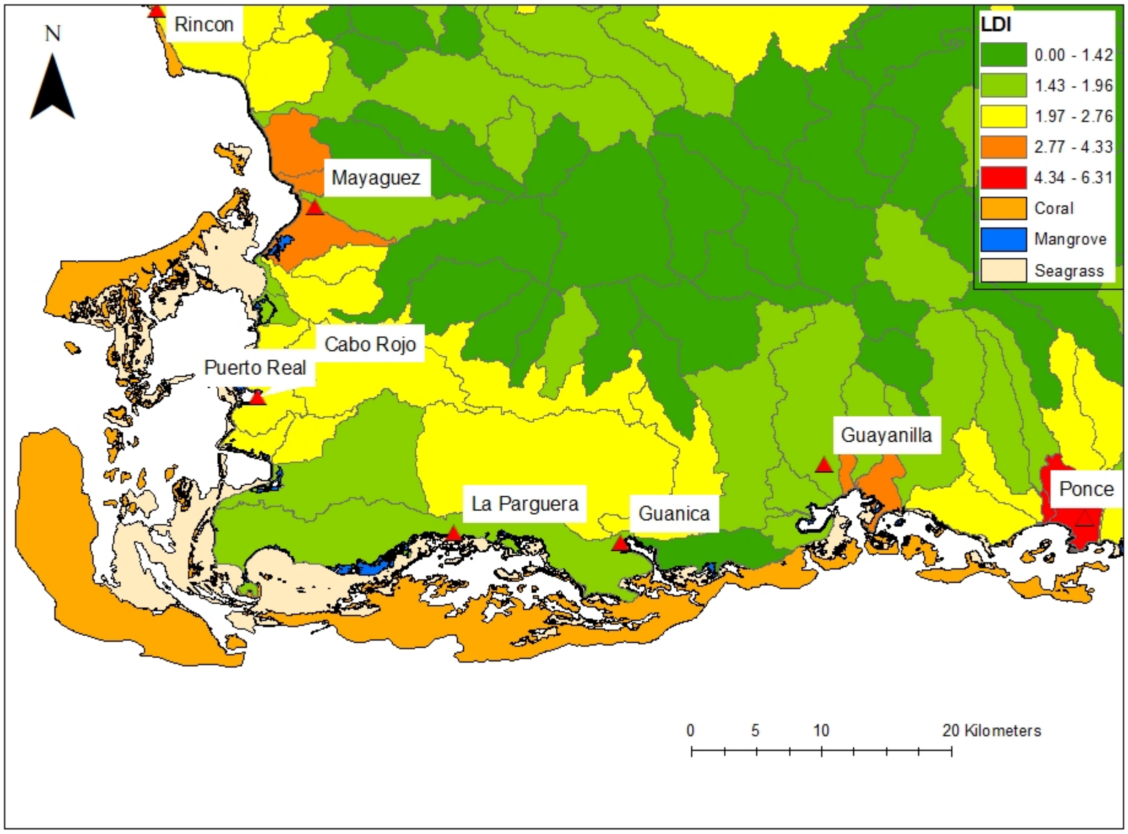


Figure S2. Hydrologic Unit Code (HUC12) watersheds of SE Puerto Rico and associated LDI values, and coastal habitats from Kendall et al. 2001. Coastal cities of SE Puerto Rico shown for reference.

Appendix T – Investigating BCG Attribute VII for Evaluating Stony Coral Condition and Disease Impacts.

Final Report, U.S. Geological Survey Interagency Agreement DW-14-92426101
Note: This is a Restricted-File Interagency Report (RFFIR). The text cannot be modified. The authors welcome discussion - please submit any discussion comments in an email, citing the line number that you are commenting upon.

Task: Development of Tools to Assess the Biological Condition in Streams, Rivers, Wetlands, Estuarine, and Near Coastal Aquatic Systems

Subtask: Biological Criteria Program—Development of Biological Condition Gradient (BCG) for Coral Reef Ecosystems

Final Report 2020

Caroline S Rogers, PhD., U.S. Geological Survey, Wetland and Aquatic Research Center, St. John, U.S. Virgin Islands, caroline_rogers@usgs.gov

Deborah L. Santavy, PhD., U.S. Environmental Protection Agency (US EPA), Office of Research and Development (ORD), Center for Environmental Measurement and Modeling (CEMM), Gulf Ecosystem Measurement and Modeling Division (GEMMD), Gulf Breeze, Florida 32561, santavy.debbie@epa.gov

Christina Horstmann, MS, ORISE Participant, Oak Ridge Institute for Science Education Participant, US EPA, ORD, CEMM, GEMMD, Gulf Breeze, Florida 32561, horstmann.christina@epa.gov

Executive Summary

The Biological Condition Gradient (BCG) model can be used to provide a foundation for managers to make informed decisions in cases involving coral reefs. Coral reefs are often referred to as "the rain forests of the sea." Although this is usually in reference to the high diversity that characterizes both of these ecosystems, the comparison is particularly appropriate because it is the corals and the trees that create the ecosystems, and the condition of these organisms (along with the actual species characteristics) will drive the ecosystem services that the forests and reefs provide. In this sense, the reefs are more similar to this structurally complex terrestrial ecosystem than to the freshwater systems, including rivers, streams, and lakes, to which the BCG framework model previously has been applied.

Coral reef managers look to scientists to provide a foundation for making informed decisions when assigning value to different coral reef systems. The critical information is the species composition, the particular species that are present (for example, major framework-building species versus "weedy" species with smaller, more fragile colonies), the abundance (numbers of individuals or "cover"), and the condition (intact, diseased, bleached, or overgrown by algae). Beyond the data that can be obtained from standard monitoring, the net calcification of a reef area would be valuable to know—that is, is the reef accreting or eroding?

The susceptibilities/tolerances of coral species to different anthropogenic stressors cannot be determined in a rigorous way because the scientific knowledge is still very limited. Coral species cannot be rigorously assigned to different attributes (I–V) that will be accurate over all stressors or even just to sedimentation/turbidity stress.

This discussion focuses on sedimentation and, to a lesser degree, warming seawater temperatures (thermal stress). Numerous other factors can adversely affect corals and other reef organisms. Examples include those factors that humans can control, such as vessel groundings and use of destructive fishing gear, and other factors out of human control, such as physical damage from storms.

Diseases are sometimes, but not always, associated with elevated temperatures and thermal stress; some research suggests links with pollution and degraded water quality, but more research is needed. More declines in living coral have been associated with diseases than any other factor.

Organism (coral) condition, the subject of this report, is particularly important in the context of coral reefs because framework-building corals are colonial, modular organisms that create the physical architecture of the reef and can persist for decades in spite of partial mortality. The species present (with the exception of *Acropora palmata* and *Orbicella* species [spp.]) are of less importance in general than the condition of the colonies and their responses as documented by long-term monitoring, when feasible.

"A Practitioner's Guide to the Biological Condition Gradient" (U.S. Environmental Protection Agency, 2016) focused on freshwater systems, and the six levels described do not include any mention of diseases or any other organism condition before level 5.

We recommend that organism condition be specifically mentioned in all levels of the BCG for coral reefs with reference to prevalence of tissue loss diseases. The ongoing devastation from stony coral tissue loss disease (initially in Florida and now in Puerto Rico and the U.S. Virgin Islands, as well as elsewhere in the Caribbean) is of paramount concern.

Benthic experts did not link disease prevalence explicitly to the six BCG levels. We propose the following for consideration and further discussion: level 1 (0–1 percent); level 2 (greater than [>] 1–5 percent); level 3 (>5–10 percent); level 4 (>10–20 percent); level 5 (>20–30 percent); and level 6 (>30 percent).

The presence and condition of *Acropora palmata* and *Orbicella* spp can provide a better basis for evaluating the overall condition of a reef area in the study locations used for this exercise than the status of other coral species. The presence of "standing dead" *Acropora palmata* provides insights into the "ecological history" of a reef site. (Occurrence is confined typically to depths less than 10 meters because this species does not usually occur in greater depths.) The number of coral species (diversity, richness) is informative but not defining.

For this discussion, the focus has been on fore reef zones in Puerto Rico < 20 m deep for which U.S. EPA monitoring data for 2010 and 2011 were available.

Although we acknowledge their obvious importance when evaluating overall reef condition, physiological changes to coral hosts or microbiota (with the exception of bleaching) are not addressed at length in this report, which focuses on visible changes in structure.

The application of the BCG model to coral reefs differs from that in freshwater systems. For example, the relative abundance of different coral species, including the major framework builders, is more indicative than the presence/absence of species with different tolerances/rarity/sensitivities that are considered indicators of the various BCG levels in freshwater systems.

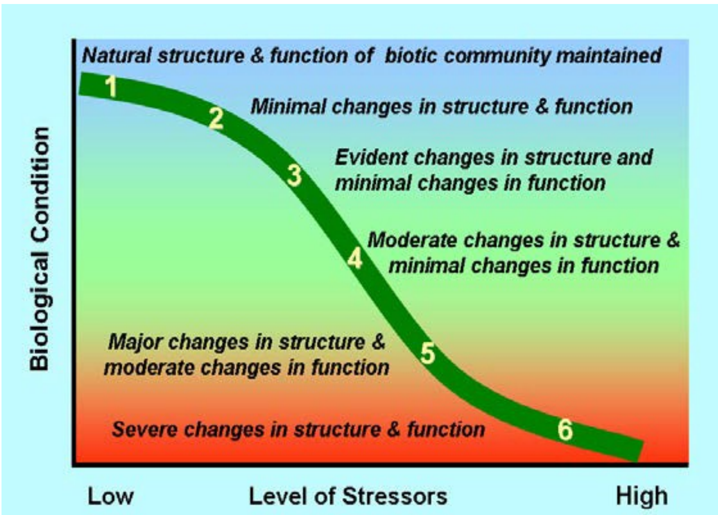
To be useful, the BCG approach should allow managers to evaluate, rank, and (or) compare different reef areas that are or were subject to various stressors. The evaluation of a site could differ greatly depending on whether or not it was based on a single survey (a "snapshot") or on successive surveys of randomly selected permanent sampling units (transects) in a long-term monitoring program (Rogers and Miller, 2016).

Introduction

The U.S. Environmental Protection Agency (U.S. EPA) has successfully used the Biological Condition Gradient model (BCG) to assess the biotic condition of freshwater streams, lakes, and wadeable river ecosystems (EPA 2016). Inherent in the BCG approach is the concept of a gradient of biological responses to the cumulative effects of multiple anthropogenic stressors (fig. 1). Our objective is to evaluate the feasibility of using this approach to characterize the biological condition of Caribbean coral reefs in a consistent way that aids managers in making informed environmental decisions. With this goal in mind, several workshops and webinars were conducted by the EPA with a group of scientists considered experts in this field (referred to as "experts" hereafter) (Bradley et. al. 2014b).

Figure 1. Conceptual model of the Biological Condition Gradient. The relation between stressors and their cumulative effects on the biota is likely nonlinear.

The BCG framework illustrates biological condition as observable or measurable changes in an ecosystem in response to anthropogenic stress. The BCG describes a gradient of six biological



condition levels, ranging from undisturbed or natural (BCG level 1) to highly disturbed or degraded conditions (BCG level 6) (fig. 1). Changes are described by departures from natural or undisturbed condition using observable biological and ecological attributes and metrics. The biological condition or BCG condition level is developed using metrics for each of six BCG condition levels (1–6) using the generic descriptions defined in table 1.

Table 1: General descriptions of the Biological Condition Gradient levels (modified from Davies and Jackson, 2006), used as guidelines by expert panel to describe narrative condition levels for coral reefs referred to BCG levels 1–6.

BCG level	General changes	Descriptions
Level 1	Natural or native condition	Native structural, functional, and taxonomic integrity is preserved; ecosystem function is preserved within the range of natural variability. BCG Level 1 represents biological conditions as they existed (or still exist) in the absence of measurable effects of stressors, and it provides the basis for comparison to the next five levels.
Level 2	Minimal changes in structure of the biotic community and minimal changes in ecosystem function	Virtually all native taxa are maintained with some changes in biomass and/or abundance; ecosystem functions are fully maintained within the range of natural variability. Level 2 represents the earliest changes in densities, species composition, and biomass that occur during a slight increase in stressors (such as increased temperature regime or nutrient enrichment).
Level 3	Evident changes in structure of the biotic community and minimal changes in ecosystem function	Evident changes in structure of the biotic community and minimal changes in ecosystem function—Some changes in structure due to loss of some rare native taxa; shifts in relative abundance of taxa, but intermediate sensitive taxa are common and abundant; ecosystem functions are fully maintained through redundant attributes of the system. Level 3 represents readily observable changes that, can occur in response to organic enrichment or increased temperature.
Level 4	Moderate changes in structure of the biotic community with minimal changes in ecosystem function	Moderate changes in structure because of replacement of some sensitive-ubiquitous taxa by more tolerant taxa but reproducing populations of some sensitive taxa are maintained; overall balanced distribution of all expected major groups; ecosystem functions largely maintained through redundant attributes.
Level 5	Major changes in structure of the biotic community and moderate changes in ecosystem function	Sensitive taxa are markedly diminished; conspicuously unbalanced distribution of major groups from distributions expected; organism condition shows signs of physiological stress; ecosystem function shows reduced complexity and redundancy. Increased buildup or export of unused materials. Changes in ecosystem function (as indicated by marked changes in food web structure and guilds) are critical in distinguishing between Levels 4 and 5.
Level 6	Severe changes in structure of the biotic community and major loss of ecosystem function	Extreme changes in structure; wholesale changes in taxonomic composition; extreme alterations from normal densities and distributions; organism condition is often poor; ecosystem functions are severely altered. Level 6 systems are taxonomically depauperate (low diversity or reduced number of organisms) compared to the other levels.

The characteristics used to define each BCG level are referred to as BCG attributes (I–X), and they were selected to measure biological condition as recommended by an expert panel of scientists. The generalized descriptions of 10 attributes defined and used for freshwater systems are in table 2. In stream and river biological assessments, most surveys are conducted at the spatial scale of a site or reach, and temporal scales can range from a season to a single sampling event. Many of the freshwater BCG attributes span these spatial and temporal scales. Spatial scale attributes at a site include measures or indicators of stressor sensitivities of various taxonomic compositions and community structures (BCG attributes I–V), non-native species (BCG attribute VI), organism condition (BCG attribute VII), and organism and system performance (BCG attribute VIII). At larger temporal and spatial scales, physical-biotic interactions (attributes IX and X) are also included because of their importance for evaluating longer-term impacts, determining restoration potential, and tracking recovery in specific water bodies (EPA 2016).

The objectives for this subtask are to define, develop, and apply BCG attribute VII (organism condition) to coral reef ecosystems, targeting scleractinian corals. This attribute considers the condition of corals at the colony, population (single species), and community (all coral species) levels. This report presents recommended characteristics for assessing coral condition exposed to human disturbances, including changing climate.

Modification of the BCG Framework for Application to Coral Reefs

In attempts to apply the BCG framework to benthic organisms on coral reefs, it became clear that BCG attributes I–V, as defined for freshwater streams and wadeable rivers, required significant modification. The freshwater BCG attributes are based on community structure and compositional complexity which typically include measures of the number, type, and proportion of individual taxa within an assemblage (for example, benthic macroinvertebrates, algae, fish, and so forth) to characterize the biological sensitivity to cumulative effects of multiple stressors. BCG attributes I–V consider which taxa are highly, intermediately, or minimally sensitive to anthropogenic stressors, focusing on the presence or absence (and in some cases the relative abundance) of taxa.

Coral reef experts concluded that many benthic, sessile marine invertebrates on coral reefs are modular organisms and must be considered differently than solitary (individual) organisms[1] that are more highly organized and mobile, such as insect larvae and macroinvertebrates residing in freshwater systems (Santavy et. al. 2016). Responses of coral populations and communities to increasing stress do not appear to be incremental or to follow a predictable sequence of changes reflected by species turnover and replacement as documented in freshwater stream benthic fauna. With increasing anthropogenic disturbance, coral species are unlikely to be replaced by other coral species with the same functional roles but different stressor tolerances. In higher quality freshwater systems, sensitive taxa and their larvae persist, but they are replaced in lower quality streams by more tolerant taxa or those with more "adaptable" life strategies. In contrast, a coral

[1] A solitary organism lives independently and has all of the functions needed to survive and reproduce (Jackson, 1977).

colony subjected to a stressor often loses only some of its tissue, resulting only in partial colony mortality (fig. 2).

The tolerance levels and responses of many coral species to exposures to individual and cumulative stressors are largely unknown, as are the life history characteristics for many. As a result, the coral reef experts were reluctant to assign all scleractinian species to a BCG attribute level ranging from I–V reflecting different sensitivities to stressors such as increasing temperature and sedimentation. Consequently, the experts included many aspects of coral colony condition (currently undefined in BCG attribute VII for coral reefs) when developing narrative BCG condition levels (1–6) for which more data are available. There is a need to formally consider and recommend descriptions, metrics, and indicators to incorporate into a coral reef BCG. The generalized descriptions for BCG attributes pertaining to organism condition are as follows: VII—"anomalies of the organisms; indicators of individual health (for example, deformities, lesions, tumors); and VIII—"processes performed by ecosystems, including primary and secondary production; respiration; nutrient cycling; decomposition; their proportion/dominance; and what components of the system carry the dominant functions, for example, shift of lakes and estuaries to phytoplankton production and microbial decomposition under disturbance and eutrophication" (table 2; Davies and Jackson, 2006).

Table 2. Biological and other ecological attributes used to characterize the freshwater streams Biological Condition Gradient (BCG) (Modified from Davies and Jackson, 2006).

Attribute	Description
I. Historically documented, sensitive, long-lived, or regionally endemic taxa	Taxa known to have been supported according to historical, museum or archeological records, or taxa with restricted distribution (occurring only in a locale as opposed to a region), often due to unique life history requirements (e.g., Sturgeon, American Eel, Pupfish, Unionid mussel species).
II. Highly sensitive (typically uncommon) taxa	Taxa that are highly sensitive to pollution or anthropogenic disturbance. Tend to occur in low numbers, and many taxa are specialists for habitats and food type. These are the first to disappear with disturbance or pollution (e.g., most stoneflies, Brook Trout [in the east], Brook Lamprey).
III. Intermediate sensitive and common taxa	Common taxa that are ubiquitous and abundant in relatively undisturbed conditions but are sensitive to anthropogenic disturbance/pollution. They have a broader range of tolerance than Attribute II taxa and can be found at reduced density and richness in moderately disturbed stations (e.g., many mayflies, many Darter fish species).
IV. Taxa of intermediate tolerance	Ubiquitous and common taxa that can be found under almost any conditions, from undisturbed to highly stressed stations. They are broadly tolerant but often decline under extreme conditions (e.g., filter-feeding caddisflies, many midges, many Minnow species).
V. Highly tolerant taxa	Taxa that typically are uncommon and of low abundance in undisturbed conditions but that increase in abundance in disturbed stations. Opportunistic species able to exploit resources in disturbed stations. These are the last survivors (e.g., tubificid worms, Black Bullhead).
VI. Non-native or intentionally introduced species	Any species not native to the ecosystem (e.g., Asiatic clam, zebra mussel, Carp, European Brown Trout). Additionally, there are many fish native to one part of North America that have been introduced elsewhere.
VII. Organism condition	Anomalies of the organisms; indicators of individual health (e.g., deformities, lesions, tumors).
VIII. Ecosystem function	Processes performed by ecosystems, including primary and secondary production; respiration; nutrient cycling; decomposition; their proportion/dominance; and what components of the system carry the dominant functions (for example, shift of lakes and estuaries to phytoplankton production and microbial decomposition under disturbance and eutrophication).
IX. Spatial and temporal extent of detrimental effects	The spatial and temporal extent of cumulative adverse effects of stressors (for example, groundwater pumping in Kansas resulting in change of fish composition from fluvial dependent to sunfish).
X. Ecosystem connectivity	Access or linkage (in space/time) to materials, locations, and conditions required for maintenance of interacting populations of aquatic life; the opposite of fragmentation. For example, levees restrict connections between flowing water and floodplain nutrient sinks (disrupt function); dams impede fish migration, spawning.

BCG Attributes

Two of the BCG attributes are relevant to this task. They are described below verbatim as presented in “A Practitioner’s Guide to the Biological Condition Gradient: A Framework to Describe Incremental Change in Aquatic Ecosystems” (EPA 2016). Although this task focuses primarily on BCG attribute VII, that attribute cannot be considered in complete isolation from BCG attribute VIII, as they are now described.

Attribute VII: Organism Condition

Organism condition is an element of ecosystem function, expressed at the level of anatomical or physiological characteristics of individual organisms. Organism condition includes direct and indirect indicators such as fecundity, morbidity, mortality, growth rates, and anomalies (for example, lesions, tumors, and deformities). Some of these indicators are readily observed in the field and laboratory, whereas the assessment of others requires specialized expertise and much greater effort.

Organism condition can also change with season or life stage or occur as short-term events making assessment difficult. The most common approach for State programs is to forego complex and demanding direct measures of organism condition (for example, fecundity, morbidity, mortality, disease, growth rates) in favor of indirect or surrogate measures (for example, percent of organisms with anomalies, age or size class distributions) (Simon, 2003). Organism anomalies in the BCG vary from naturally occurring incidence in levels 1 and 2 to higher than expected incidence in levels 3 and 4. In levels 5 and 6, biomass is reduced, the age structure of populations indicates premature mortality or unsuccessful reproduction, and the incidence of serious anomalies is high. This attribute has been successfully used in stream indices based on the fish assemblage (Yoder and Rankin, 1995; Sanders et. al. 1999).

Attribute VIII: Ecosystem Function

Ecosystem function refers to any processes required for the performance of a biological system expected under naturally occurring conditions. Naturally occurring conditions have been interpreted typically as those conditions found in undisturbed to minimally disturbed sites, but some processes can be sustained under moderate levels of disturbance. Examples of ecosystem functional processes are primary and secondary production, respiration, nutrient cycling, and decomposition. Assessing ecosystem function includes consideration of the aggregate performance of dynamic interactions within an ecosystem, such as the interactions among taxa (e.g., food web dynamics) and energy and nutrient processing rates (e.g., energy and nutrient dynamics) (Cairns, 1977).

Additionally, ecosystem function includes aspects of all levels of biological organization

(individual, population, and community condition). Altered interactions between individual organisms and their abiotic and biotic environments might generate changes in growth rates, reproductive success, movement, or mortality. These altered interactions are ultimately expressed at ecosystem levels of organization (for example, shifts from heterotrophy to autotrophy, onset of eutrophic conditions) and as changes in ecosystem process rates (for example, photosynthesis, respiration, production, decomposition).

At this time, the level of effort required to directly assess ecosystem function is beyond the means of many State monitoring programs. Instead, in streams and wadeable rivers, most programs rely on taxonomic and structural indicators to make inferences about functional status (Karr et. al. 1986). For example, shifts in the primary source of food might cause changes in trophic guild indices or indicator species. Although direct measures of ecosystem function are currently difficult or time consuming, they might become practical in the future (Gessner and

Chauvet, 2002). The BCG conceptual model includes an attribute for ecosystem function for future application.

Recommendations for Defining Ambiguous or Unclear Terms in the Definition of BCG Attributes VII and VIII

When applying the BCG framework to coral reef ecosystems, we suggest that these attributes may require some further specification and clarification. For example, the distinction between "direct" and "indirect" measures of organism condition is not entirely clear in the definitions (EPA 2016). It is also helpful to differentiate between structural and functional characteristics. Odum (1962) provided the following definitions:

> "By structure we mean: 1) The composition of the biological community including species, numbers, biomass, life history and distribution in space of populations; 2) the quantity and distribution of the abiotic (non-living) materials such as nutrients, water, etc.; and 3) the range, or gradient, of conditions of existence such as temperature, light, etc."
>
> "By function we mean 1) the rate of biological energy flow through the ecosystem, that is, the rates of production and the rates of respiration of the populations and the community; 2) the rate of material or nutrient cycling, that is, the biogeochemical cycles,
>
> 3) biological or ecological regulation including both regulation of organisms by environment (as, for example, in photoperiodism) and regulation of environment by organisms (as, for example, in nitrogen fixation by microorganisms)."

In addition, partial or entire mortality and the presence of disease lesions can be seen macroscopically in the field (structural), while changes in coral growth and fecundity (functional) cannot. Thermal stress can lead to bleaching, and prolonged bleaching can result in reduced growth and reproductive failure (Szmant and Gassman, 1990; Weil et. al. 2009a). Although only incidence is mentioned in the current description of attribute VII, prevalence is also important and more often documented. Incidence is the number of new diseased individuals in a specified population during a specified time period, and prevalence is the percent of diseased individuals in a population at a point in time (Stedman, 2006). Incidence is a rate and conveys information about the risk of contracting the disease, whereas prevalence indicates the proportion of individuals affected at a particular time.

Evaluation of Coral Reef Status Based on Condition of Scleractinian Corals

What can we learn about the overall condition of a coral reef by examining individual coral colonies? Can we quantify and characterize different reef conditions based on an evaluation of numerous colonies from several coral species at a single point in time or over several successive surveys? Diseases certainly are a primary focus for attribute VII. Diseases are often referred to as causes of coral mortality, but they are in fact the end result of sometimes unknown stressors, such as nutrient input. Burial by sediments and physical damage from storms and anchors are other examples of conspicuous changes to corals that would influence the evaluation/ranking of a reef area.

Physical damage to corals can result from storms but also from vessel groundings, careless snorkelers or SCUBA divers, and fishing gear. Physical damage to corals from major storms can increase disease prevalence (Bright et. al. 2016). Coral species differ in their vulnerability to damage, with branching species more likely to become fragmented. Anchor damage can result in complete pulverization of coral colonies (Rogers and Garrison, 2001). In some coral species, however, fragmentation can result in an increase in colonies and in wider distribution.

Most scientists agree that a combination of changing climate and destructive human actions are contributing to degradation of coral reefs (Intergovernmental Panel on Climate Change, 2014). Climate change has many components, including elevated ocean temperature, sea level rise, and increased intensity and perhaps frequency of major storms and hurricanes. The BCG workshop experts made a critical decision to include increasing seawater temperature associated with changing climate as an anthropogenic stressor in developing the BCG model for coral reefs.

Rising seawater temperature is one of the most significant stressors affecting coral reefs globally today. Reports of up to 40 percent coral mortality caused by elevated temperature with associated bleaching have occurred on the northern portion of the Great Barrier Reef since January 2016 (Hughes et. al. 2018; Eakin et. al. 2019). More alarming forecasts predict that coral bleaching episodes are expected to become more frequent in the future (Hoegh-Guldberg, 1999; Eakin et. al. 2019; Skirving et. al. 2019).

The greatest loss in coral cover in the last 50 years on reefs in the U.S. Virgin Islands and Puerto Rico has been from an outbreak of diseases following bleaching associated with the highest seawater temperatures on record in the Caribbean in 2005. More than 90 percent of the corals bleached in late summer of 2005, with some recovery occurring as temperatures cooled in November 2005. A subsequent coral disease outbreak resulted in losses of more than 60 percent of the coral cover by 2007 (Miller et. al. 2009). A similar pattern of bleaching, recovery, and disease was seen in Puerto Rico at that time (Ballantine et. al. 2008; Weil et. al. 2009b). This illustrates how regional stressors, such as high seawater temperatures for extended periods of time, often have greater effects on coral reef ecosystems compared to local stressors such as sewage runoff which would affect smaller areas. When regional and local stressors are present, the outcome on the coral communities is usually much more severe than when single stressors act independently (Hoegh-Guldberg et. al. 2007).

Ocean acidification, decreasing pH caused by increasing atmospheric carbon dioxide, is another major concern that can result from climate change. Global warming associated with changing climate fuels the increase in the frequency and severity of hurricanes. Hurricanes Irma and Maria, both in September 2017, were especially destructive in shallow, nearshore areas in Puerto Rico and the U.S. Virgin Islands. However, declines in coral cover have been linked more to coral diseases than any other stressor, with the potential for even more loss of living coral with the advance of Stony Coral Tissue Loss Disease (Weil 2019).

Responses to Stressors

One of the many challenges of applying BCG attributes I–V to coral reefs is the essential nature of corals themselves—modular, colonial organisms, portions of which can persist over time after other portions die. A coral colony with only one-half of the skeleton covered with live tissue can survive for decades, whereas one-half of a fish or a mayfly will not persist at all. In some cases, coral colonies die partially, and new tissue regenerates over the skeleton making it impossible to tell that the coral ever lost any tissue at all (fig. 2).

Evaluating coral condition is complicated by the fact that re-sheeting can occur, hiding any evidence that there was mortality in the first place. In other cases, loss of coral tissue occurs gradually and inconspicuously in the absence of any obvious disease or predation and without exposure of distinct white skeletal areas reflecting loss of coral tissue revealing the underlying skeleton (fig. 3a–d). This situation may result from some type of coral/algal interaction or even transfer of a pathogen from the algae (Nugues et. al. 2004). Only very careful and frequent (photographic) monitoring of individual colonies over time (weeks or months) would discern such situations. In general, loss of coral tissue from any cause is followed by settlement of filamentous algae which is followed by macroalgae, particularly when grazing rates by herbivorous fish and urchins are low. Macroalgae can inhibit settlement of coral recruits contributing to overall reef decline (McCook et. al. 2001; Jompa and McCook, 2002; Diaz-Pulido et. al. 2010).

Morbidity[2] and mortality[3] follow very different mechanisms in clonal and solitary organisms, such that in solitary organisms the mortality is complete; none of the organism is functional. If affected by disease, morbidity can lead to mortality, depending on which organs are affected. In modular organisms, the mortality of individual polyps can be a sign of morbidity, but infection with disease does not necessarily lead to total mortality of the colony. Furthermore, the death of a colony does not always mean the extinction of that particular genotype. If ramets (physically separated colonies of the same genotype resulting from asexual reproduction) are dispersed over the reef, the genet (genotype) has a higher probability of surviving the disturbance.

Diseases

Coral diseases are increasing in number and severity (Weil and Rogers 2011). Burge and others (2013) noted: “The biological and physical changes to the world’s oceans, coupled with other anthropogenic influences, will likely lead to more opportunistic diseases in the marine environment.” Disease has a broad definition. Based on Stedman (2006 and earlier references therein), Peters (1997) defined disease as “any impairment (interruption, cessation, proliferation, or other disorder) of vital body functions, systems, or organs,” and added that “Diseases are usually characterized either by (1) an identifiable group of signs (observed anomalies indicative of disease), and/or (2) a recognized etiologic or causal agent, and/or (3) consistent structural alterations (e.g.

[2] Morbidity is the state of being ill or in diseased state (Stedman, 2006).
[3] Mortality is another term for death (Stedman, 2006).

developmental disorders, changes in cellular composition or morphology and tumors).” Diseases result from complicated interactions among the host, the environment, and an abiotic or biotic agent. The number of diseases of scleractinian corals and octocorals in the Caribbean/western Atlantic exceeds 20 (Sutherland et. al. 2004; Weil, 2004; Weil and Rogers, 2011; Weil et. al. 2017) with other less well defined or characterized conditions referred to as “compromised health conditions” (Raymundo et. al. 2008; Weil and Hooten, 2008).

Bleaching is a disease under the definition presented above. For the purposes of this report, we use the term disease in almost all cases to refer to cases where tissue is lost originating from a lesion, and the term bleaching to refer to the appearance of coral colonies that have lost the symbiotic zooxanthellae or zooxanthellae pigments (fig. 4), a condition which does not necessarily lead to morbidity and mortality.

Corals only have few visible signs of stress. Thermal stress leads to paling or bleaching with recovery possible if the stress is removed over a short enough time period. Bleaching is a sign of stress, typically a thermal anomaly (high or low temperatures), but corals can recover. There are degrees of bleaching, with colonies ranging from slightly pale, to blotched and completely white. Single surveys of bleaching cannot provide a complete picture of the reef’s condition. In general, it is not as alarming as the appearance of new disease lesions.

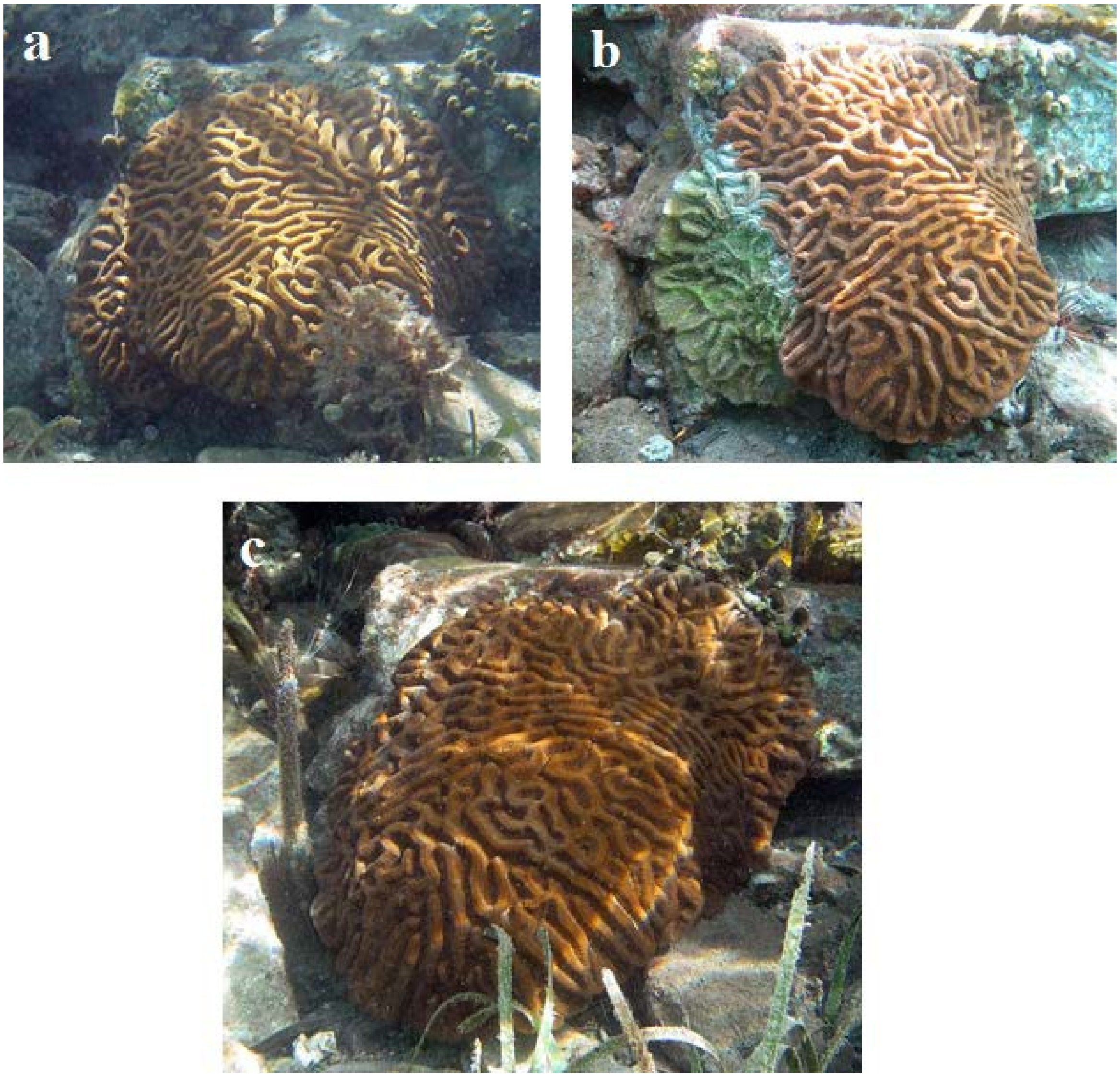


Figure 2. A colony of *Colpophyllia natans* in St. John, U.S. Virgin Islands (a) with no sign of disease (August 8, 2009), (b) with white plague disease and fireworm predation (February 15, 2010), and (c) after tissue regenerated over the exposed skeleton (re-sheeting) (November 25, 2012).

Coral species differ in their susceptibility to thermal stress and therefore in the likelihood of bleaching and mortality (McClanahan et. al. 2009) (fig. 5). Within the Caribbean, different coral species and even different colonies within a species can host several different symbiotic algal *Symbiodinium* clades and therefore exhibit dissimilar responses to thermal stress (Thornhill et. al. 2014; Kemp et. al. 2015). Susceptibility to bleaching is not equivalent to likelihood of mortality.

Many diseases are associated with bright white bands, patches, and irregular areas where the coral skeleton is exposed following loss of tissue and are characterized based on these lesions: the shape (for example, linear), the location (for example, near the apex, base), virulence (fast, slow), and distribution (for example, multifocal) (Work and Aeby, 2006). In some cases, red, black, and white bands and dark spots are on the colonies. Pathogens include bacteria, ciliates

(Sweet and Séré, 2015), and viruses (Soffer et. al. 2014), although pathogens have been identified for only a few diseases (Weil and Rogers, 2011).

A few diseases have been particularly devastating in Puerto Rico: black band, white plague, and Caribbean yellow band. Coral diseases are complicated, involving not only the coral host but also the associated symbiotic zooxanthellae and other microorganisms and the environment. A coral can be infected with a disease before showing visible signs. Some studies document shifts in microbial communities over time as coral colony condition changes, and others compare microbial communities found in nondiseased corals with those in stressed or diseased corals (Frias-Lopez et. al. 2002, 2004; Pantos et. al. 2003; Pantos and Bythell, 2006; Sekar et. al. 2006; Bourne et. al. 2008; Sunagawa et. al. 2009; Tracy et. al. 2015). When corals become bleached and (or) diseased, pathogenic microbes sometimes replace beneficial microbes (Ritchie, 2006). Diseased samples were similar in bacterial community composition in colonies from Florida and the U.S. Virgin Islands; in contrast, major differences in bacterial assemblages were found from apparently healthy colonies of *Orbicella faveolata* and *Orbicella franksi* and on those with signs of white plague, but not between the two coral species (Roder et. al. 2014). Recent comprehensive discussions of coral diseases include Weil and Rogers (2011) and Raymundo and others (2008). In the Pacific, a large number of conditions are grouped simply under the term “white syndromes,” but in the Caribbean, some diseases are distinct enough to warrant more specific names, such as white band disease, black band disease, dark spots disease, and Caribbean yellow band disease. In many cases it is unclear if different pathogens are producing the same signs, or if different signs appear in response to the same pathogen in different species or under varying environmental conditions. The case of the pathogen for white pox illustrates that the etiology of a disease can change over time, further complicating efforts to diagnose understand the causes of, and eventually respond to and attempt to manage stressors linked to coral diseases (Sutherland et. al. 2016). The severity of white pox, for example has varied during the past 20 years, with greater mortality of entire coral colonies in the earlier years.

Diseases are affecting almost all coral species, including the “foundation” species, those that are most responsible for the physical architecture of coral reefs (Szmant and Gassman, 1990; Aronson and Precht, 2001a; Sutherland et. al. 2004; Weil et. al. 2009a, b; Ruiz-Moreno et. al. 2012; Rogers and Miller, 2013). In some cases, these “structural engineers” have had disproportionately higher mortality during bleaching and (or) disease events (Cróquer and Weil, 2009; McClanahan et. al. 2009; Miller et. al. 2009; Weil et. al. 2009a, b; Bastidas et. al. 2012; Bruckner, 2012; Ruiz-Moreno et. al. 2012).

A particularly devastating disease, called Stony Coral Tissue Loss Disease (SCTLD) has been ravaging reefs along the Florida Reef Tract since 2014 (Precht et. al. 2016; Gintert et. al. 2019; Weil 2019). The Atlantic and Gulf Rapid Reef Assessment website (http://www.agrra.org) provides updates on spatial distribution and other aspects of the disease. A video available at https://youtu.be/H-WIs4J2oW8 provides helpful background information about SCTLD. In January 2019, this or a similar disease was observed off western St. Thomas, and over the course of 1 year, it spread east to western St. John. Ballast water from a ship out of Florida was released in waters near where this disease was first observed in St. Thomas and may be linked to this outbreak (U.S. Coast Guard, 2019). This disease is affecting almost all coral species except the acroporids. Research continues on identification of the pathogen which could provide clues as to a possible link between water quality and the disease. Monitoring of coral colonies near a large construction project at Port Miami (Florida) documented more mortality from disease than from dredging effects (Gintert et. al. 2019).

The actual causes of most coral diseases remain elusive. Increasing seawater temperatures, high sedimentation, untreated sewage effluent, introduced pathogen species, and more frequent and (or) intense storms could all lead to more coral loss from diseases. Although diseases have been observed far from major human population centers, some links between diseases and human-caused stressors like sedimentation and nutrient runoff have been proposed (Weil et. al. 2002; Kaczmarsky et. al. 2005; Wooldridge and Done, 2009; Sutherland et. al. 2010). Some studies have linked specific pathogens to diseases; some of these pathogens are linked to human actions, and therefore, are presumably manageable (Sutherland et. al. 2010).

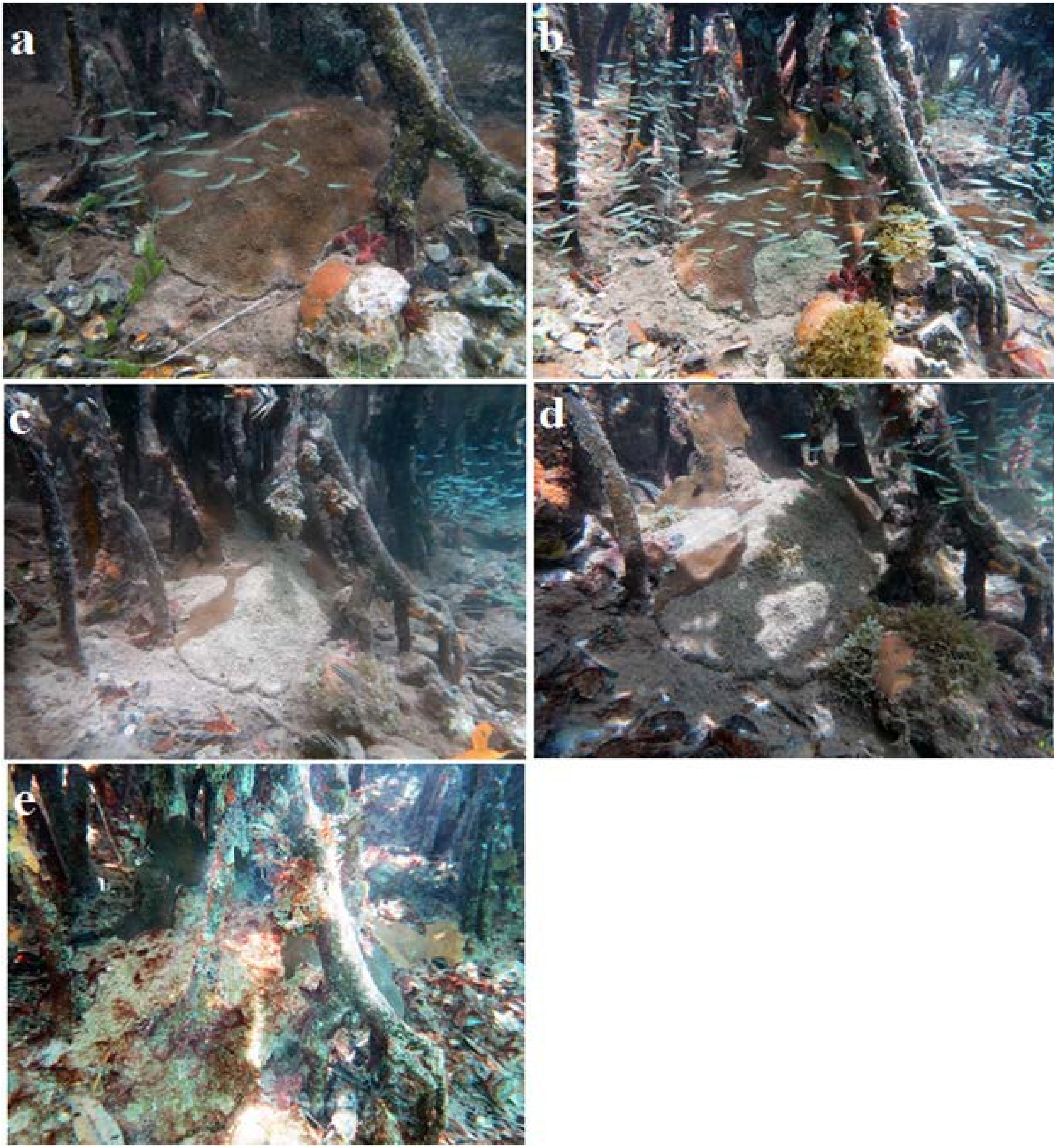


Figure 3. *Orbicella faveolata* colony with increasing loss of tissue in the absence of conspicuous disease, St. John, U.S. Virgin Islands: (a) March 30, 2013; (b) May 18, 2014; (c) May 31, 2015; (d) June 16, 2015; and (e) October 2, 2015.

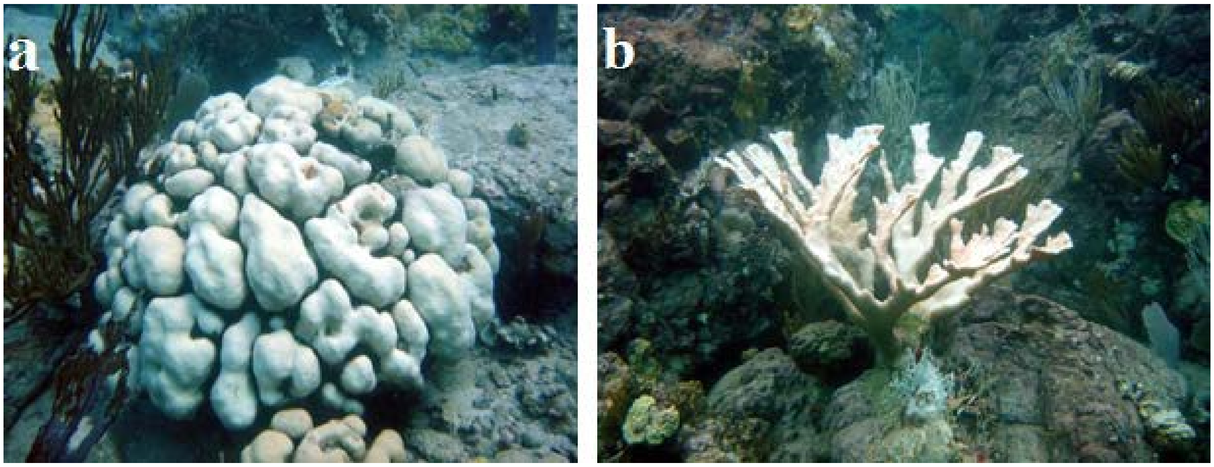


Figure 4. Bleached colonies of (a) *Orbicella annularis* and (b) *Acropora palmata.* (Photographs by E. Muller, U.S. Geological Survey.)

Figure 5. Coral species differ in their susceptibility to bleaching (following thermal stress) as seen in these adjacent *Colpophyllia natans* (upper) and *Diploria labyrinthiformis* (lower) colonies.

Prevalence

As noted earlier, “A Practitioner’s Guide to the Biological Condition Gradient” (EPA 2016) describes BCG levels 1–6 for freshwater systems. The guide makes no specific mention of organism condition until level 5. Increasing degradation from level 1 to level 6 is based on changes in richness and density of taxa with varying degrees of rarity and tolerance. The description for level 5 states “organism condition shows signs of physiological stress” and “changes in organism condition (attribute VII) may include significantly increased mortality, depressed fecundity, and/or increased frequency of lesions, tumors, and deformities” (EPA 2016). This is the first mention of diseases in the guide. Given the importance of organism condition for corals, the building blocks of coral reefs, we recommend that prevalence values be proposed for each of the six levels. Note that the term "prevalence" is strictly used for populations of single species, but some scientists find "overall" or "community level" prevalence, here defined as the number of coral colonies of all species with disease, which is a useful characterization (Rogers 2010).

Benthic experts did not discuss disease prevalence but we suggest the following for further consideration: level 1: 0 to 1 percent; level 2: >1 to 5 percent; level 3: >5 to 10 percent; level 4: >10 to 20 percent; level 5: >20 to 30 percent; level 6: > 30 percent.

If we accept that some disease is likely to occur even in the absence of any major stressors, what are "normal" levels of disease prevalence? Strictly, prevalence should be calculated separately for each coral species and each disease combination, but often scientists have presented prevalence values for all species and diseases combined. Yee et al. (2011) cautioned investigators about considering the underlying assumptions when prevalence was calculated by pooling data from different coral species and assuming similarities in disease susceptibility when interpreting disease risk. They demonstrated the potential erroneous outcomes from using simulated data to assess the ability of standard statistical methods (binomial and linear regression, analysis of variance) to detect a significant environmental effect on pooled disease prevalence with varying species abundance distributions and relative susceptibilities to disease.

Prevalence values of less than 10 percent have been referred to as "low," but if these are calculated annually from the same reef and different colonies are diseased at each survey, clearly there should be cause for alarm because this could signal higher disease incidence and a potential epizootic. Santavy and others (2005) found that reporting the prevalence of diseases at both the population and community levels was a useful biological indicator for coral reef condition. For example, 79 percent of the reefs in South Florida had less than 6 percent of the coral colonies diseased, whereas only 2.2 percent of the sampled area had a maximum prevalence of 13 percent diseased coral colonies at any single location. Santavy and others (2005) suggested a background of 6 percent coral disease prevalence for the Florida Keys during the early 2000s but cautioned that many factors must be considered and more detailed and frequent studies must be completed to increase certainty.

Weil and Rogers (2011) present prevalence values for individual coral species and diseases ranging from 0.002 percent for white patch disease (white pox) to 25 percent for white band disease -II (table 3). Higher values for white patch disease on *Acropora palmata* have been reported from St. John (Muller et. al. 2008; Rogers and Muller, 2012) and from Florida (Sutherland et. al. 2016).

Few studies examine prevalence or coral loss from diseases over long periods of time. As one example, the U.S. National Park Service (NPS) scientists are conducting long-term monitoring of coral reefs in parks in Florida and the U.S. Virgin Islands (Biscayne National Park, Dry Tortugas National Park, Virgin Islands National Park, and Buck Island Reef National Monument). The primary focus has been on changes in cover of corals and other benthic organisms. Since about 2005, NPS scientists have also been recording the number and total area of disease lesions by coral species along each long-term transect, usually once a year. These data can be compared over time and among sites. They provide a measure of virulence (severity) and overall prevalence of disease (but not by coral species).

Sedimentation Stress

Ranking of coral species by sensitivity to turbidity, and sediment deposition requires caution. Many papers make references to "sediment tolerant" coral species or interpret their findings with differential sensitivity in mind (Erftemeijer et. al. 2012), but a closer look reveals that the evidence for differential response to increased levels of sedimentation is quite limited. Controlled laboratory studies cannot reflect the wide range of field conditions, and field studies are typically based on rather small sample sizes.

Some publications provide information on vulnerabilities of coral species to various stressors, but limited data are available (Erftemeijer et. al. 2012; National Oceanic and Atmospheric Administration, 2012). Many studies have documented responses of corals to stressors that are not macroscopic (visible) but rather involve microscopic changes, such as shifts in microbial communities (Vega Thurber et. al. 2009) and gene expression (DeSalvo et. al. 2008). There may be techniques in the future which will allow an evaluation of the coral conditions which are sublethal or not visible (Ricaurte et. al. 2016).

Although we are still exploring the evidence for varying sensitivities and their applicability to the BCG, currently the assigning of different attribute levels to coral species does not appear to be an effective foundation for ranking a reef site. We suggest that the condition of the coral colonies of the major framework-building species is the most informative indicator of the overall status of a reef site. Coral species vary in their overall morphology, growth rates, maximum size, and other characteristics. Some species contribute far more to the structure and function of a reef than others, such as the large branching, massive, and brain corals. Corals in the genus *Orbicella* (formerly *Montastraea*) often contribute more to the living "cover" on Caribbean coral reefs than many of the other species (Kemp et. al. 2015).

Coral Demographics

Models that predict the population dynamics of solitary organisms incorporate age-dependent rates of birth, death, and migration into and out of the population. However, such models do not apply to sessile clonal organisms such as corals with variable rates in growth, recruitment (settlement and survival), fission, fusion, and partial mortality along with high longevity (Hughes and Connell 1987). The combined effects of growth, partial mortality, and recruitment, all of which can be affected by environmental conditions, might be noticeable through shifts in population structure (Meesters et. al. 2001). By quantifying these parameters, studies can detect gradual decreases in the condition of communities and can potentially provide information about a reef's future state (Smith et. al. 2005). Size-frequency distributions (numbers of colonies within each size class) can help reveal small- or large-scale processes in the population and in the drivers of those processes (Hughes and Connell, 1987; Hughes and Tanner, 2000; Gilmour, 2004; Smith et. al. 2005; Edmunds and Elahi, 2007). Size-frequency distributions vary with the type, intensity, and frequency of the stressor or environment to which the populations have been exposed (Gilmour, 2004). When an entire hard coral community is assessed, the sizes within "age classes" vary due to the differences in growth rate, maximum colony size, and resilience among coral species (Hughes, 1984).

Colony size is an important life-history trait, but age and size are not well correlated in corals because of partial mortality and fusion (Hughes, 1984; Hughes and Jackson, 1985). Stressors that reduce colony size have consequences for reproduction and population dynamics because the number of fertile polyps in colonies determines their fecundity and larger colonies tend to have more sexually mature polyps (Hughes, 1984; McClanahan et. al. 2008; Harrison, 2011). A lack of juveniles might be attributed to low survivorship of post-settlers due to multiple environmental/biological stressors, especially the conditions at the time of mass spawning and settlement, which will influence survival of larvae.

Because population size structure is greatly influenced by the environment, it can be used in some cases as evidence of an unfavorable or degraded habitat (Meesters et. al. 2001; Gilmour, 2004; Alvarado-Chacon and Acosta, 2009). However, populations dominated by small individuals may indicate either a population with high recruitment or one that has high fragmentation of larger colonies due to environmental stress. If no small colonies are found, conditions are not favorable for successful settlement and recruitment, and the population cannot sustain itself (Bak and Meesters, 1999; Alvarado-Chacon and Acosta, 2009). Many studies have found that populations are dominated by larger colonies at degraded sites, likely because of a lack of recruitment and (or) low survival of small colonies (Bak and Meesters, 1998; Meesters et. al. 2001; Smith et. al. 2005; McClanahan et. al. 2008). Overall, a balanced range of size classes is advantageous to maintain a functioning reef (Alvarado-Chacon and Acosta, 2009).

To understand the processes that drive size-frequency distributions of populations, it is important to determine how environmental conditions affect individuals of different sizes. Besides the life-history characteristics of each species, colony size is highly influenced by the environment and the associated stressors (Hughes, 1984; Meesters et. al. 2001). It has been suggested that small colonies are more susceptible to instantaneous or acute whole-colony mortality and if partially injured, their chances of recovery are low (Hughes and Connell, 1987; Hughes and Tanner, 2000). This could be due to smaller colonies having lower amounts of energy reserved and less material to transfer to damaged polyps (Hughes and Connell, 1987). Therefore, if there is a stressor, small colonies have a high probability of either escaping injury or dying completely, whereas large colonies have a low chance of escaping at least some partial mortality. Certain stressors such as sediment burial or overgrowth by competitors are more likely to harm small colonies. These two stressors are usually seen as indicators of poor water quality; therefore, large numbers of small colonies could indicate good water quality (Smith et. al. 2005).

Table 3. Coral reef diseases in the western Atlantic Ocean (modified from Weil and Rogers, 2011). [Year, year reported/observed; P/A, pathogen/agent identified, Y (yes) or N (no); CO, corals; OC, octocorals; HY, hydrocorals; SP, sponges; ZO, zoanthids; CCA, crustose coralline algae; DE, depth distribution; m, meter; PR, average community prevalence; %, percent; TM, tissue mortality rate; mm/day, month/day; - not observed; GD, geographic distribution; WA, western Atlantic; WC, wider Caribbean; VI, Virgin Islands; FL, Florida; BE, Bermuda; CA, Caribbean; BA, Bahamas; ME, Mexico; PR, Puerto Rico; CU, Curacao; CY, Caymans]

Disease	Acronym	Year	P/A	Number of taxa showing disease signs (Brazilian species)									
				CO	OC	HY	ZO	SP	CCA	DE (m)	PR (%)	TM (mm/day)	GD
Bleaching	BL	1911	N	62	29	5	2	8	-	0–100	0.2–85	-	WA
Coral growth anomalies	CGA	1965	N	10	8	1	-	-	-	0–25	-	-	WC
Black band disease	BBD	1973	Y	19(4)	6	-	-	-	-	0–25	0.3–6	3–10	WA
White band disease-I	WBDI	1977	N	2	-	-	-	-	-	0–10	0.1	-	WC
White plague disease-I	WPDI	1977	N	12	-	-	-	-	-	10–21	3.6	3.1	FL
Shut Down reaction	SDR	1977	N	6	-	-	-	-	-	5–12	-	-	FL
White band disease-II	WBDII*	1982	Y	3	-	-	-	-	-	1–25	0.1–25	3–30	WC not BE
Red band disease	RBD	1984	Y	13(1)	5	-	-	-	-	2–20	-	1	WA
Acropora serriatosis[1]	ASER*	1992	Y	1	-	-	-	-	-	0–5	0.002	15	CA,FL,BA
Caribbean yellow band [a]	YBD *	1994	Y	11	-	-	-	-	-	3–20	1–24	0.1–0.4	WC
White plague disease-II	WPDII*	1995	Y	41(5)	-	2	-	-	-	3–30	0.9–18	3–30	WA
Aspergillosis	ASP*	1996	Y	-	9	-	-	-	-	1–25	1.9	0.1–2.5	WA
Dark spots disease	DSD	2001	N	11(1)	-	-	-	-	-	1–25	1.1	-	WA
Caribbean white syndromes[2]	CWS	2004	N	15	-	2	1	3	-	2–25	-	-	WC[a]
Caribbean ciliate infection	CCI	2006	Y	21	-	-	-	-	-	2–25	-	-	WC[a]
Octocoral growth anomalies	OGA	1977	Y	-	8	-	-	-	-	2–22	-	-	WC
Gorgonia labyrinthulomycosis[3]	LAB	2008	Y	-	2	-	-	-	-	4–20	-	-	FL, PR
Multi-focal purple spots[4]	MFPS	2015	Y	-		-	-	-	-	3–22	-	-	ME,FL,CA
Briareum bleaching necrosis	BBN	1998	N	-	2	-	-	-	-	5–15	-	-	FL, PR
Briareum wasting syndrome	BWS	1999	N	-	2	-	-	-	-	5–15	-	-	FL,PR,CU
Gorgonia wasting syndrome	GWS	2010	N	-	1	-	-	-	-	3–20	10	-	PR
Palythoa wasting syndrome	PAWS	2008	Y	-	-	-	-	-	-	3–10	-	-	WC
Erythropodium wasting syndrome	EWS	2005	N	-	1	-	-	-	-	3–22	-	-	PR-CY-CU
Phyllogorgia wasting syndrome	PWS	2013	N	-	1	-	-	-	-	5–12	73	-	BR
Crustose-Coralline white syndrome	CCWB	2004	N	-	-	-	-	-	3	1–20	1–6	0.1–2	WC[a]
Crustose-Coralline lethal orange dis.	CCLOD	2008	N	-	-	-	-	-	1	12–22	-	-	PR,CY,ME
Other coral syndromes[5]	OCS	-	N	15	-	-	-	-	-	1–25	-	-	WA
Other octocoral syndromes[5]	OOS	-	-	-	8	-	-	-	-	3–20	-	-	WC

* Koch's postulates fulfilled.

1 White patch disease is also termed white pox and patchy necrosis.

2 White syndromes include several patterns of tissue loss exposing bands, stripes, blotches, or irregular shapes of clean skeleton (different from the other "white" diseases) with very low prevalence.

3 Purple spots produced by an unknown protozoan (Labyrinthulomycota.

4 Health conditions of other corals and octocorals include unhealthy-looking tissues with some degree of mortality, low prevalence and limited geographic distribution with no pathological or etiological information.

a Includes Flower Gardens Banks National Marine Sanctuary. Western Atlantic distribution includes the wider Caribbean and Brazil. Bleaching-affected species from Brazil have not been included .

Unfortunately, size-frequency distributions are still not considered a strong measure of coral reef condition. They can be ambiguous and hard to interpret, more so if no historical information from the reef is available. For example, increasing frequencies of small colonies can either be the result of recruitment (and [or] fragmentation) and survivorship, which is a beneficial process, or a result of partial mortality, which is the result of a stressor (Miller et. al. 2016). Especially if a population is only measured once, it can be misleading because populations are strongly influenced by recent events and the processes that influence size structure are often temporally variable. Measuring long-term size-frequency distribution fluctuations in response to different types and levels of disturbance can provide much better insights into population dynamics than a single size-frequency distribution alone.

Programs such as the Florida Reef Resilience Program and the Atlantic and Gulf Rapid Reef Assessment only started implementing colony size surveys in the early 2000s (Fisher et. al. 2008; Miller et. al. 2016). Measuring coral demographics can provide vital information on a population that more traditional percent cover surveys cannot. Ideally, long-term surveys of size-frequency measurements and of percent cover would be done together to provide a more accurate indication of the condition of a reef.

The Importance of Context

The condition of the coral colonies must be included when ranking coral reefs or reef zones in terms of their position along a stress gradient (levels 1–6 in the BCG model). In fact, we suggest that the condition of the coral colonies of the major framework-building species is the single most informative indicator of the overall status of a reef site. Rules developed for application of the BCG model for evaluating and ranking the reefs should not be considered individually or in isolation; context will be vitally important here. A recently proposed rule states that reefs at level 2 would have a coral cover of >45 percent (table 4). The coral cover for the reference (natural) condition has not been defined, partly because high-quality data, collected randomly from numerous and widely distributed reefs, are not available. Coral cover on Caribbean reefs now (as of 2012) ranges from 2.8 percent to 53.1 percent (mean of 16.8 percent) (Jackson et. al. 2014, p. 65).

To be useful, the BCG approach should allow managers to evaluate, rank, and (or) compare different reef areas that are or were subject to various stressors. The evaluation of a site could differ greatly depending on whether it was based on a single survey (a “snapshot”) or on successive surveys in a long-term monitoring program.

Recommendation:
To gain insights into how the coral experts derived scores for different reefs, it would be valuable to get their opinion on different hypothetical habitats. For example, how would they evaluate the following habitats (assuming each reef has the same number of colonies)? How would the evaluations and the rankings change with different coral species present?

- A reef with 75 percent coral cover and with 90 percent of the corals bleached.

- A reef in which 10 percent of the colonies of one framework-building (or other) species has disease versus a reef in which 10 percent of the colonies of all species have disease.
- A reef with 75 percent coral cover and with 50 percent of the corals exhibiting new diseases.
- A reef with 50 percent coral cover and 75 percent of the colonies with high levels of old partial mortality.
- A reef with 25 percent coral cover with colonies showing no visible signs of disease or effects of other stress.
- A reef with 50 percent of the corals exhibiting white plague disease versus a reef with 75 percent of the corals exhibiting black band disease.

The BCG is "a framework to describe incremental change in aquatic ecosystems" (EPA 2016). What evidence is there that coral reefs change incrementally? Are there "thresholds" that separate levels 1 to 6? Experts concluded that algal cover might be useful for determining "thresholds or tipping points for BCG levels for coral benthic community assessments" (Bradley and Santavy, 2016, p. B-70). Very few papers document changes in percent cover or disease prevalence over time, and most are from the U.S. Virgin Islands (Muller et. al. 2008; Miller et. al. 2009; Rogers and Muller, 2012). These papers can be examined carefully to see if any thresholds are revealed.

<u>Recommendation</u>:

Have the experts examine the data from the NPS long-term (randomly selected, permanent) monitoring transects collected during the last 15–20 years. Data are in Miller and others (2009) and in NPS Inventory and Monitoring Annual reports.

- Select individual transects (perhaps ones that differ the most) and examine how the rankings compare.
- Compare results from before and after the 2005/2006 bleaching and disease event to reveal any consistent patterns. Are these patterns in agreement with the report by Jackson and others (2014)?
- Are there declines in coral cover over time with comparable macroalgal increases? Despite considerable discussion about phase shifts, some review papers do not support this as a general pattern in the Caribbean (Bruno et. al. 2009).

While further investigation into the scientific literature might provide more clues as to species resistance to different stressors, it is not evident that corals can be assigned as readily as many other organisms to a particular location on the response gradient. The condition of the major reef-building genera should be given the highest priority.

Table 4. Benthic coral reef Biological Condition Gradient (BCG) narrative rules proposed by the expert panel, but not thoroughly vetted. This table is still under discussion and development by benthic experts.

[>, greater than, ≥, greater than or equal to; cm, centimeter; ≤, less than or equal to; spp., more than one species; sp., species]

	Narrative
BCG Level 2	
Stony corals	• >45 percent live cover of coral in fore reef habitat • Minimal recent mortality in large reef-building genera (*Orbicella, Pseudodiploria, Colpophyllia, Acropora, Dendrogyra, P. porites*) • Normal frequency distribution of colony sizes within each species size range to include large, medium, and small colonies (≥4 cm) and presence of recruits (≤4 cm) • Species composition and diversity composed of sensitive, rare species (*Isophyllia, Isophyllastrea, Mycetophyllia. Eusmilia, Scolymia*) present in appropriate habitat type • Very low or just background levels of disease, tissue and skeletal anomalies, and bleaching • Large *Orbicella* (fore reef), *Acropora* (back reef, reef crest, reef slope) colonies dominate reef structure within respective zones
Rugosity	• High rugosity resulting from large living coral colonies, producing spatial and topographical complexity
Macroinvertebrates	• *Diadema* abundant • Reef macroinvertebrates (e.g., Lobsters, crabs, conch) common and abundant • Low levels of invertebrate coral predators (*Coralliophila spp, Hermodice sp*)
Algae	• Minimal fleshy, filamentous, and cyanobacterial algae present • Crustose coralline algae present, with some turf algae
Sponges	• Phototrophic sponges dominate (abundant) • Low frequency of Clionid boring sponges
BCG Level 3	
Stony corals	• >25 percent live cover of coral in appropriate habitat • Higher percentage of tissue loss with signs of recent mortality especially on large reef-building genera (*Orbicella, Pseudodiploria, Colpophyllia, Acropora, Dendrogyra*) • Frequency distribution of colony sizes within each species size range starting to become skewed to include fewer very large, medium and small colonies (≥4 cm) and lower number of recruits than expected (≤4 cm) • Species composition and diversity: sensitive, rare species present in appropriate habitat. Moderate abundance of hydrocorals in shallower habitats • Low to moderate levels of disease and bleaching • *Orbicella* and *Acropora* colonies still dominant (within respective reef geomorphological zones)
Rugosity	• Moderate to high rugosity or reef structure resulting from large living reef-forming and dead coral colonies, producing spatial complexity (or topographical heterogeneity)
Macroinvertebrates	• *Diadema* present abundant • Reef macroinvertebrates (e.g., Lobsters, octopus, conch) present, low densities
	• Minimal to moderate presence of fleshy, filamentous, and cyanobacterial algae cover

Algae	• Crustose coralline and turf algae present
	• Phototrophic sponges present and abundant
Sponges	• Low cover and abundance of Clionid boring sponges
BCG Level 4	
Stony corals	• >15 percent live cover of coral in appropriate habitat • Moderate amount of recent partial or total colony mortality on reef-building genera (*Orbicella, Pseudodiploria, Acropora, Dendrogyra)* • Mix of sizes: large colonies may be absent, primarily medium and small colonies • Species composition and diversity: sensitive spp may be absent (*Agaricia, Mycetophyllia, Colpophyllia*, *Isophyllia*, etc.), more tolerant spp present (*Montastraea cavernosa, Siderastrea siderea, Porites astreoides*; *P. porites* at least some reef-building corals present but not dominant (primarily *Orbicella*) • Moderate to high levels of disease and potential bleaching on corals and sea fans/branching gorgonians
Rugosity	• Rugosity due to old mostly dead coral structure
Macroinvertebrates	• *Palythoa* may be present, but not dominant
Algae	• Moderate to high amount of fleshy, filamentous and cyanobacterial algae cover
Sponges	• Moderate cover and abundance of Clionid boring sponges
BCG Level 5	
Stony corals	• >1 percent live cover of coral in appropriate habitat • High recent tissue mortality on corals present or organisms absent. Low amount of live tissue remains.
Rugosity	• Low rugosity, and that which is present may be due to old dead coral structure
Algae	• Coral cover mostly replaced by fleshy, filamentous and cyanobacterial algae
Macroinvertebrates	• *Palythoa* dominant
Sponges	• Highest presence of Clionid boring sponges • Low abundance and size of phototrophic sponges, non-phototrophic dominant

EndNote Bibliographic Database

Dr. Rogers and Dr. Santavy combined their electronic reference libraries (more than 2,000 EndNote references) relating to coral reef organism condition, coral diseases, and responses to different anthropogenic stressors and began building the bibliographic database by selecting pertinent articles. In addition, Christina Horstmann searched for papers on coral reef stressors through Google Scholar and also by checking citations in the bibliographies of papers that were already in the database. Overall, the database has 783 references, 90 percent of which have Portable Document Format (PDF) files attached and 95 percent of which are journal articles. There are 51 groups that organize key topics. Within those groups there are two main stressor categories: stressors related to climate change (266 references) and land-based stressors (180 references). The main groups related to organism condition are disease and bleaching, and those categories have about 370 references. Most references fall into multiple groups. References are labeled as field studies, lab studies, metadata studies, or reviews. The lab studies have quantitative data with specific species and stressor intensities, whereas 75 percent of the field studies are observational and involve multiple stressors on the community level. References are also sorted by location, with 80 percent of studies done in the Caribbean. In addition, about 280 references are government reports and general coral reef ecology studies which include topics such as community structure and biodiversity. In studies that focus on specific stressors, the coral species and the stressor type, intensity, duration, and effects are all provided to aid in possibly identifying thresholds for the coral species.

Acknowledgments

Our thanks to Ernesto Weil (University of Puerto Rico) and Amanda Demopoulos (U.S. Geological Survey) for their constructive comments during their reviews of this report.

References Cited

Alvarado-Chacon, E., and Acosta, A., 2009, Population size-structure of the reef-coral *Montastraea annularis* in two contrasting reefs of a marine protected area in the southern Caribbean Sea: Bulletin of Marine Science, v. 85, no. 1, p. 61–76.

Aronson, R.B., and Precht, W.F., 2001, White-band disease and the changing face of Caribbean coral reefs: Hydrobiologia, v. 460, p. 25–38.

Bak, R.P., and Meesters, E.H., 1998, Coral population structure—The hidden information of colony size-frequency distributions: Marine Ecology Progress Series, v. 162, p. 301–306.

Bak, R.P., and Meesters, E.H., 1999, Population structure as a response of coral communities to global change: American Zoologist, v. 39, no. 1, p. 56–65.

Ballantine, D.L., Appeldoorn, R.S., Yoshioka, P., Weil, E., Armstrong, R., Garcia, J.R., Otero, E., Pagan, F., Sherman, C., Hernandez-Delgado, E.A., Bruckner, A., and Lilyestrom, C., 2008, Biology and ecology of Puerto Rican coral reefs, chap. 9 *of* Riegl, B.M., and Dodge, R.E., eds., Coral reefs of the world (v. 1): Berlin, Springer, p. 375–406.

Bastidas, C., Bone, D., Croquer, A., Debrot, D., Garcia, E., Humanes, A., Ramos, R., and Rodríguez, S., 2012, Massive hard coral loss after a severe bleaching event in 2010 at Los Roques, Venezuela: Revista de Biologia Tropical, v. 60, no. 1, p. 29–37.

Bourne, D., Iida, Y., Uthicke, S., and Smith-Keune, C., 2008, Changes in coral-associated microbial communities during a bleaching event: The ISME Journal, v. 2, p. 350–363.

Bradley, P., and Santavy, D.L., 2016, Caribbean coral reefs—Benchmarking a Biological Condition Gradient for Puerto Rican coral reefs, *in Appendices to* A practitioner's guide to the Biological Condition Gradient—A framework to describe incremental change in aquatic ecosystems: U.S. Environmental Protection Agency EPA 842-R-16-001, p. B53–B76.

Bradley, P., Santavy, D.L., and Gerritsen, J., 2014, Workshop on Biological Integrity of Coral Reefs [Proceedings of a workshop on biological integrity of coral reefs, Caribbean Coral Reef Institute, Isla Magueyes, La Parguera, Puerto Rico, August 21–22, 2012]: Narragansett, R.I.,

U.S. Environmental Protection Agency, Office of Research and Development, Atlantic Ecology Division, EPA/600/R-13/350.
Bright, A.J., Rogers, C., Brandt, M., Muller, E., and Smith, T., 2016, Disease prevalence and snail predation associated with swell-generated damage on the threatened coral, *Acropora palmata* (Lamarck): Frontiers in Marine Science, v. 3, no. 77, 13 p.
Bruckner, A.W., 2012, Factors contributing to the regional decline of *Montastraea annularis* (complex), *in* International Coral Reef Symposium, 12th, Cairns, Australia, July 9–13, 2012, Proceedings: Annapolis, Md., The Khaled bin Sultan Living Oceans Foundation, 5 p.
Bruno, J.F., Sweatman, H., Precht, W.F., Selig, E., and Schutte, V.C.W., 2009, Assessing evidence of phase shifts from coral to macroalgal dominance on coral reefs: Ecology, v. 90, no. 6, p. 1478–1484.
Burge, C.A., Kim, C.J.S., Lyles, J.M., and Harvell, C.D., 2013, Special issue oceans and human health—The ecology of marine opportunists: Microbial Ecology, v. 65, p. 869–879.
Cairns, J., Jr., 1977, Quantification of biological integrity, *in* Ballentine, R.K., and Guarria, L.J., eds., The integrity of water—Proceedings of a symposium: Washington, D.C., U.S. Environmental Protection Agency, p. 171–187.
Cróquer, A., and Weil, E., 2009, Changes in Caribbean coral disease prevalence after the 2005 bleaching event: Diseases of Aquatic Organisms, v. 87, no. 1, p. 33–43.
Davies, S.P., and Jackson, S.K., 2006, The Biological Condition Gradient—A descriptive model for interpreting change in aquatic ecosystems: Ecological Applications, v. 16, no. 4, p. 1251–1266.
DeSalvo, M.K., Voolstra, C.R., Sunagawa, S., Schwarz, J.A., Stillman, J.H., Coffroth, M.A., Szmant, A.M., and Medina, M., 2008, Differential gene expression during thermal stress and bleaching in the Caribbean coral *Montastraea faveolata*: Molecular Ecology, v. 17, no. 17, p. 3952–3971.
Diaz-Pulido, G., Harii, S., McCook, L.J., and Hoegh-Guldberg, O., 2010, The impact of benthic algae on the settlement of a reef-building coral: Coral Reefs, v. 29, no. 1, p. 203–208.
Eakin, C.M., Sweatman, H.P.A., and Brainard, R.E., 2019, The 2014–2017 global-scale coral bleaching event—Insights and impacts: Coral Reefs, v. 38, p. 539–545.
Edmunds, P.J., and Elahi, R., 2007, The demographics of a 15-year decline in cover of the Caribbean reef coral *Montastraea annularis*: Ecological Monographs, v. 77, no. 1, p. 3–18.
Erftemeijer, P.L., Riegl, B., Hoeksema, B.W., and Todd, P.A., 2012, Environmental impacts of dredging and other sediment disturbances on corals—A review: Marine Pollution Bulletin, v. 64, no. 9, p. 1737–1765.
Fisher, W.S., Fore, L.S., Hutchins, A., Quarles, R.L., Campbell, J.G., LoBue, C., and Davis, W.S., 2008, Evaluation of stony coral indicators for coral reef management: Marine Pollution Bulletin, v. 56, no. 10, p. 1737–1745.
Frias-Lopez, J., Klaus, J.S., Bonheyo, G.T., and Fouke, B.W., 2004, Bacterial community associated with black band disease in corals: Applied and Environmental Microbiology, v. 70, no. 10, p. 5955–5962.
Frias-Lopez, J., Zerkle, A.L., Bonheyo, G.T., and Fouke, B.W., 2002, Partitioning of bacterial communities between seawater and healthy, black band diseased, and dead coral surfaces: Applied and Environmental Microbiology, v. 68, no. 5, p. 2214–2228.

Gessner, M.O., and Chauvet, E., 2002, A case for using litter breakdown to assess functional stream integrity: Ecological Applications, v. 12, no. 2, p. 498–510.

Gilmour, J.P., 2004, Size-structures of populations of the mushroom coral *Fungia fungites*—The role of disturbance: Coral Reefs, v. 23, no. 4, p. 493–504.

Gintert, B.E., Precht, W.F., Fura, F., Rogers, K., Rice, M., Precht, L.L., D'Alessandro, M., Croop, J., Vilmar, C., and Robbart, M.L., 2019, Regional coral disease outbreak overwhelms impacts from a local dredge project: Environmental Monitoring and Assessment, v. 191, article no. 630.

Harrison, P.L., 2011, Sexual reproduction of Scleractinian corals, *in* Dubinsky, Z., and Stambler, N., eds., Coral reefs—An ecosystem in transition: Dordrecht, Netherlands, Springer, p. 59–85.

Hoegh-Guldberg, O., 1999, Climate change, coral bleaching and the future of the world's coral reefs: Marine and Freshwater Research, v. 50, no. 8, p. 839–866.

Hoegh-Guldberg, O., Mumby, P.J., Hooten, A.J., Steneck, R.S., Greenfield, P., Gomez, E., Harvell, C.D., Sale, P.F., Edwards, A.J., Caldeira, K., and Knowlton, N., 2007, Coral reefs under rapid climate change and ocean acidification: Science, v. 318, no. 5857, p. 1737–1742.

Hughes, T.P., 1984, Population dynamics based on individual size rather than age—A general model with a reef coral example: The American Naturalist, v. 123, no. 6, p. 778–795.

Hughes, T.P., Anderson, K., Connolly, S., Heron, S., Kerry, J., Lough, J., Baird, A., Baum, J., Berumen, M., Bridge, T., Claar, D., Eakin, C.M., Gilmour, J., Graham, N., Harrison, H., Hobbs, J.P., Hoey, A., Hoogenboom, M., Lowe, R., McCulloch, M., Pandolfi, J., Pratchett, M., Schoepf, V., Torda, G., and Wilson, S., 2018, Spatial and temporal patterns of mass bleaching of corals in the Anthropocene: Science, v. 359, no. 6371, p. 80–83.

Hughes, T.P., and Connell, J.H., 1987, Population dynamics based on size or age? A reef-coral analysis: The American Naturalist, v. 129, no. 6, p. 818–829.

Hughes, T.P., and Jackson, J.B.C., 1985, Population dynamics and life histories of foliaceous corals: Ecological Monographs, v. 55, no. 2, p. 141–166.

Hughes, T.P., and Tanner, J.E., 2000, Recruitment failure, life histories, and long-term decline of Caribbean corals: Ecology, v. 81, no. 8, p. 2250–2263.

Intergovernmental Panel on Climate Change, 2014, Climate change 2014—Synthesis report, contribution of working groups I, II and III to the 5th assessment report of the Intergovernmental Panel on Climate Change, *in* Pachauri, R.K., and Meyer, L.A., eds., Intergovernmental Panel on Climate Change: Geneva, Switzerland, 167 p.

Jackson, J., Donovan, M., Cramer, K., and Lam, V., eds., 2014, Status and trends of Caribbean coral reefs—1970–2012: Gland, Switzerland, Global Coral Reef Monitoring Network, International Union for Conservation of Nature, 306 p.

Jackson, J.B.C., 1977, Competition on marine hard substrate—The adaptive significance of solitary and colonial strategies: The American Naturalist, v. 111, no. 980, p. 743–767.

Jompa, J., and McCook, L.J., 2002, Effects of competition and herbivory on interactions between a hard coral and a brown alga: Journal of Experimental Marine Biology and Ecology, v. 271, no. 1, p. 25–39.

Kaczmarsky, L.T., Draud, M., and Williams, E.H., 2005, Is there a relationship between proximity to sewage effluent and the prevalence of coral disease? Caribbean Journal of Science, v. 41, no. 1, p. 124–137.

Karr, J.R., Fausch, K.D., Angermeier, P.L., Yant, P.R., and Schlosser, I.J., 1986, Assessing biological integrity in running waters—A method and its rationale, *in* Illinois Natural History Survey special publication 5: Champaign, Ill., Illinois Natural History Survey Division, 28 p.

Kemp, D.W., Thornhill, D.J., Rotjan, R.D., Iglesias-Prieto, R., Fitt, W.K., and Schmidt, G.W., 2015, Spatially distinct and regionally endemic *Symbiodinium* assemblages in the threatened Caribbean reef-building coral *Orbicella faveolata*: Coral Reefs, v. 34, p. 535–547.

McClanahan, T.R., Ateweberhan, M., and Omukoto, J., 2008, Long-term changes in coral colony size distributions on Kenyan reefs under different management regimes and across the 1998 bleaching event: Marine Biology, v. 153, p. 755–768.

McClanahan, T.R., Weil, E., Cortés, J., Baird, A.H., and Ateweberhan, M., 2009, Consequences of coral bleaching for sessile reef organisms, chap. 8 *in* van Oppen, M., and Lough, J., eds., Coral bleaching—Patterns, processes, causes and consequences: Champaign, Ill., Springer-Verlag, Ecological Studies 205, p. 121–138.

McCook, L., Jompa, J., and Diaz-Pulido, G., 2001, Competition between corals and algae on coral reefs—A review of evidence and mechanisms: Coral Reefs, v. 19, p. 400–417.

Meesters, E.H., Hilterman, M., Kardinaal, E., Keetman, M., and Bak, R.P.M., 2001, Colony size-frequency distributions of scleractinian coral populations—Spatial and interspecific variation: Marine Ecology Progress Series, v. 209, p. 43–54.

Miller, J., Muller, E., Rogers, C., Waara, R., Atkinson, A., Whelan, K.R.T., Patterson, M., and Witcher, B., 2009, Coral disease following massive bleaching in 2005 causes 60% decline in coral cover on reefs in the U.S. Virgin Islands: Coral Reefs, v. 28, p. 925–937.

Miller, M., Williams, D.E., Huntington, B.E., Piniak, G.A., and Vermeij, M.J.A., 2016, Decadal comparison of a diminishing coral community—A study using demographics to advance inferences of community status: PeerJ, v. 4, e1643.

Muller, E.M., Rogers, C.S., Spitzack, A.S., and Van Woesik, R., 2008, Bleaching increases likelihood of disease on *Acropora palmata* (Lamarck) in Hawksnest Bay, St. John, U.S. Virgin Islands: Coral Reefs, v. 27, p. 191–195.

National Oceanic and Atmospheric Administration, 2012, Endangered and threatened wildlife and plants—Proposed listing determinations for 82 reef-building coral species—Proposed reclassification of *Acropora palmata* and *Acropora cervicornis* from threatened to endangered: Federal Register, v. 77, no. 236, p. 73221–73261.

Nugues, M.M., Smith, G.W., van Hooidonk, R.J., Seabra, M.I., and Bak, R.P.M., 2004, Algal contact as a trigger for coral disease: Ecology Letters, v. 7, no. 10, p. 919–923.

Odum, E.P., 1962, Relationships between structure and function in the ecosystem: Japanese Journal of Ecology, v. 12, p. 108–118.

Pantos, O., and Bythell, J.C., 2006, Bacterial community structure associated with white band disease in the elkhorn coral *Acropora palmata* determined using culture-independent 16S rRNA techniques: Diseases of Aquatic Organisms, v. 69, no. 1, p. 79–88.

Pantos, O., Cooney, R.P., Le Tissier, M.D.A., Barer, M.R., O'Donnell, A.G., and Bythell, J.C., 2003, The bacterial ecology of a plague-like disease affecting the Caribbean coral *Montastrea annularis*: Environmental Microbiology, v. 5, no. 5, p. 370–382.

Peters, E.C., 1997, Diseases of coral-reef organisms, chap. 6 *in* Birkeland, C., ed., Life and death of coral reefs: New York, Chapman and Hall, p. 114–139.

Precht, W.F., Gintert, B.E., Robbart, M.L., Fura, R., and van Woesik, R., 2016, Unprecedented disease-related coral mortality in southeastern Florida: Scientific Reports, v. 6, no. 31374.

Raymundo, L.J., Couch, C.S., and Harvell, C.D., (eds.), 2008, Coral disease handbook—Guidelines for assessment, monitoring & management: Queensland, Australia, The University of Queensland Coral Reef Targeted Research and Capacity Building for Management Program, 124 p.

Ricaurte, M., Schizas, N.V., Ciborowski, P., and Boukli, N.M., 2016, Proteomic analysis of bleached and unbleached *Acropora palmata*, a threatened coral species of the Caribbean: Marine Pollution Bulletin, v. 107, no. 1, p. 224–232.

Ritchie, K.B., 2006, Regulation of microbial populations by coral surface mucus and mucus-associated bacteria: Marine Ecology Progress Series, v. 322, p. 1–4.

Roder, C., Arif, C., Daniels, D., Weil, E., and Voolstra, C.R., 2014, Bacterial profiling of white plague disease across corals and oceans indicates a conserved and distinct disease microbiome: Molecular Ecology, v. 23, no. 4, p. 965–974.

Rogers, C.S., 2010, Words matter—Recommendations for clarifying coral disease nomenclature and terminology: Diseases of Aquatic Organisms, v. 91, no. 2, p. 167–175.

Rogers, C.S., and Garrison, V.H., 2001, Ten years after the crime—Lasting effects of damage from a cruise ship anchor on a coral reef in St. John, U.S. Virgin Islands: Bulletin of Marine Science, v. 69, no. 2, p. 793–803.

Rogers, C.S., and Miller, J., 2013, Coral diseases cause reef decline: Science, v. 340, no. 6140, p. 1522.

Rogers, C.S., and Miller, J., 2016, Measuring, interpreting, and responding to changes in coral reefs—A challenge for biologists, geologists, and managers, *in* Hubbard, D., Rogers, C., Lipps, J., and Stanley, G., Jr., eds., Coral reefs at the crossroads, v. 6 *of* Coral Reefs of the World: Dordrecht, Netherlands, Springer, p. 277–292.

Rogers, C.S., and Muller, E.M., 2012, Bleaching, disease and recovery in the threatened scleractinian coral *Acropora palmata* in St. John, U.S. Virgin Islands—2003–2010: Coral Reefs, v. 31, p. 807–819.

Ruiz-Moreno, D., Willis, B.L., Page, A.C., Weil, E., Cróquer, A., Vargas-Angel, B., Jordan-Garza, A.G., Jordán-Dahlgren, E., Raymundo, L., and Harvell, C.D., 2012, Global coral disease prevalence associated with sea temperature anomalies and local factors: Diseases of Aquatic Organisms, v. 100, p. 249–261.

Sanders, R.S., Miltner, R.J., Yoder, C.O., and Rankin, E.T., 1999, The use of external deformities, erosions, lesions, and tumors (DELT anomalies) in fish assemblages for characterizing aquatic resources—A case study of seven Ohio streams, *in* Simon, T.P., ed., Assessing the sustainability and biological integrity of water resources using fish communities: Boca Raton, Fla., CRC Press, p. 225–248.

Santavy, D.L., Bradley, P., Gerritsen, J., and Oliver, L., 2016, The Biological Condition Gradient, a tool used for describing the condition of U.S. coral reef ecosystems, *in*

International Coral Reef Symposium, 13th, Honolulu, Hawaii, June 19–24, 2016, Proceedings: Honolulu, Hawaii, International Coral Reef Society, p. 557–568.

Santavy, D.L., Summers, J.K., Engle, V.D., and Harwell, L.C., 2005, The condition of coral reefs in South Florida (2000) using coral disease and bleaching as indicators: Environmental Monitoring and Assessment, v. 100, p. 129–152.

Sekar, R., Mills, D.K., Remily, E.R., Voss, J.D., and Richardson, L.L., 2006, Microbial communities in the surface mucopolysaccharide layer and the black band microbial mat of black band-diseased *Siderastrea siderea*: Applied and Environmental Microbiology, v. 72, no. 9, p. 5963–5973.

Simon, T.P., ed., 2003, Biological response signatures—Indicator patterns using aquatic communities: Boca Raton, Fla., CRC Press, 576 p.

Skirving, W.J., Heron, S.F., Marsh, B.L., Liu, G., De La Cour, J.L., Geiger, E.F., and Eakin, C.M., 2019, The relentless march of mass coral bleaching—A global perspective of changing heat stress: Coral Reefs, v. 38, p. 547–557.

Smith, L., Devlin, M., Haynes, D., and Gilmour, J., 2005, A demographic approach to monitoring the health of coral reefs: Marine Pollution Bulletin, v. 51, p. 399–407.

Soffer, N., Brandt, M.E., Correa, A.M., Smith, T.B., and Thurber, R.V., 2014, Potential role of viruses in white plague coral disease: The ISME Journal, v. 8, no. 2, p. 271–283.

Stedman, T.L., 2006, Stedman's Medical Dictionary (27th ed.): Baltimore, Md., Lippincott Williams & Wilkins, 2,098 p.

Sunagawa, S., DeSantis, T.Z., Piceno, Y.M., Brodie, E.L., DeSalvo, M.K., Voolstra, C.R., Weil, E., Andersen, G.L., and Medina, M., 2009, Bacterial diversity and white plague disease-associated community changes in the Caribbean coral *Montastraea faveolata*: The ISME Journal, v. 3, p. 512–521.

Sutherland, K.P., Berry, B., Park, A., Kemp, D.W., Kemp, K.M., Lipp, E.K., and Porter, J.W., 2016, Shifting white pox aetiologies affecting *Acropora palmata* in the Florida Keys, 1994–2014: Philosophical Transactions of the Royal Society B Biological Sciences, v. 371, no. 1689, article no. 20150205, 16 p.

Sutherland, K.P., Porter, J.W., and Torres, C., 2004, Disease and immunity in Caribbean and Indo-Pacific zooxanthellate corals: Marine Ecology Progress Series, v. 266, p. 273–302.

Sutherland, K.P., Porter, J.W., Turner, J.W., Thomas, B.J., Looney, E.E., Luna, T.P., Meyers, M.K., Futch, J.C., and Lipp, E.K., 2010, Human sewage identified as likely source of white pox disease of the threatened Caribbean elkhorn coral, *Acropora palmata*: Environmental Microbiology, v. 12, no. 5, p. 1122–1131.

Sweet, M.J., and Séré, M.G., 2015, Ciliate communities consistently associated with coral diseases: Journal of Sea Research, v. 113, p. 119–131.

Szmant, A., and Gassman, N.J., 1990, The effects of prolonged "bleaching" on the tissue biomass and reproduction of the reef coral *Montastrea annularis*: Coral Reefs, v. 8, no. 4, p. 217–224.

Tracy, A.M., Koren, O., Douglas, N., Weil, E., Harvell, C.D., 2015, Persistent shifts in Caribbean coral microbiota are linked to the 2010 warm thermal anomaly: Environmental Microbiology Reports, v. 7, no. 3, p. 471-479, Thornhill, D.J., Lewis, A.M., Wham, D.C., and LaJeunesse, T.C., 2014, Host-specialist lineages dominate the adaptive radiation of reef coral endosymbionts: Evolution, v. 68, no. 2, p. 352–367.

U.S. Environmental Protection Agency, 2016, A practitioner's guide to the Biological Condition Gradient—A framework to describe incremental change in aquatic ecosystems: Washington, D.C., U.S. Environmental Protection Agency, EPA-842-R-16-001, 250 p.

Vega Thurber, R.V., Willner-Hall, D., Rodriguez-Mueller, B., Desnues, C., Edwards, R.A., Angly, F., Dinsdale, E., Kelly, L., and Rohwer, F., 2009, Metagenomic analysis of stressed coral holobionts: Environmental Microbiology, v. 11, no. 8, p. 2148–2163.

Weil, E., 2004, Coral reef diseases in the wider Caribbean, *in* Rosenberg, E., and Loya, Y., eds., Coral health and disease: Heidelberg, Germany, Springer, p. 35–68.

Weil, E., Croquer, A., and Urreiztieta, I., 2009a, Temporal variability and impact of coral diseases and bleaching in La Parguera, Puerto Rico from 2003–2007: Caribbean Journal of Science, v. 45, no. 2–3, p. 221–246.

Weil, E., Cróquer, A., and Urreiztieta, I., 2009b, Yellow band disease compromises the reproductive output of the reef-building coral *Montastraea faveolata* (Anthozoa, Scleractinia): Diseases of Aquatic Organisms, v. 87, no. 1–2, p. 45–55.

Weil, E., Hernandez-Delgado, H., Gonzalez, M., Williams, S., Suleiman-Ramos, S., Figuerola, M., and Metz-Estrella, T., 2019, Spread of the new coral disease "SCTLD" into the Caribbean—Implications for Puerto Rico: Reef Encounter, v. 34, no. 1, p. 38–43.

Weil, E., and Hooten, A., 2008, Underwater cards for assessing coral health on Caribbean reefs, Global Environment Facility-Coral Reef Targeted Research Program resource: Brisbane, Australia, Center for Marine Sciences, University of Queensland, 24 p.

Weil, E., and Rogers, C.S., 2011, Coral reef diseases in the Atlantic-Caribbean, chap. 27 *in* Dubinsky, Z., and Stambler, N., eds., Coral reefs—An ecosystem in transition: Netherlands, Springer-Verlag, p. 465–491.

Weil, E., Rogers, C., and Croquer, A., 2017, Octocoral diseases in a changing sea, *in* Rossi, S., Gori, A., Orejas Seco del Valle, C., eds., Marine animal forests—The ecology of benthic biodiversity hotspots: Champaign, Ill., Springer, p. 1–55.

Weil, E., Urreiztieta, I., and Garzón-Ferreira, J., 2002, Geographic variability in the incidence of coral and octocoral diseases in the wider Caribbean, *in* International Coral Reef Symposium, Bali, Indonesia, 9th, October 23–27, 2000, Proceedings: Bali, Indonesia, International Coral Reef Society, p. 1231–1237.

Wooldridge, S.A., and Done, T.J., 2009, Improved water quality can ameliorate effects of climate change on corals: Ecological Applications, v. 19, no. 6, p. 1492–1499.

Work, T.M., and Aeby, G.S., 2006, Systematically describing gross lesions in corals: Diseases of Aquatic Organisms, v. 70, no. 1–2, p. 155–160.

Yee, S.H., Kern, J.W., Santavy, D., and Hession, D., 2011, Consideration of species community composition in statistical analyses of coral disease risk: Marine Ecology Progress Series, v. 431, p. 83–96.

Yoder, C.O., and Rankin, E.T., 1995, Biological response signatures and the area of degradation value—New tools for interpreting multimetric data, *in* Davis, W.S., and Simon, T.P., eds., Biological assessment and criteria—Tools for water resource planning and decision making: Boca Raton, Fla., Lewis Publishers, p. 263–286.