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A biological condition gradient for coral reefs in the US Caribbean Territories: Part I. Coral narrative rules

Deborah L Santavy [a], Susan K. Jackson [b], Benjamin Jessup [c], Jeroen Gerritsen [c,3], Caroline Rogers [d], William S. Fisher [a], Ernesto Weil [e], Alina Szmant [f,1], David Cuevas-Miranda [g], Brian K. Walker [h], Christopher Jeffrey [i], Patricia Bradley [c,2], David Ballantine [j], Loretta Roberson [k,4], Hector Ruiz-Torres [k,5], Brandi Todd [l,6], Tyler Smith [m], Randy Clark [n], Ernesto Diaz [o], Jorge Bauzá-Ortega [p], Christina Horstmann [q], Sandy Raimondo [a,*]

[a] *US 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, FL 32561, USA*
[b] *US EPA, Office of Water, Washington, DC, USA*
[c] *Tetra Tech, Inc., Montpelier, VT, USA*
[d] *U.S. Geological Survey, Wetland and Aquatic Research Center, St. John, VI, USA*
[e] *University of Puerto Rico, Mayaguez, PR, USA*
[f] *University of North Carolina, Wilmington, NC, USA*
[g] *US EPA, Region 2, Guaynabo, PR, USA*
[h] *Nova Southeastern University, Ft. Lauderdale, FL, USA*
[i] *CSS-Inc., Fairfax, VA, USA*
[j] *Smithsonian Institution, National Museum of Natural History, Wash. DC, USA*
[k] *University of Puerto Rico, Rio Piedras, PR, USA*
[l] *US EPA, Region 6, Dallas, TX, USA*
[m] *University of Virgin Islands, St. Thomas, VI, USA*
[n] *NOAA NCCOS, Marine Spatial Ecology Division, Biogeography Branch, Stennis Space Center, MS, USA*
[o] *DPNR Puerto Rico, EQB, San Juan, PR, USA*
[p] *San Juan Bay National Estuary Program, San Juan, PR, USA*
[q] *Oak Ridge Institute for Science Education Fellow, US EPA, ORD, CEMM, GEMMD, Gulf Breeze, FL 32561 USA*

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A B S T R A C T

As coral reef condition and sustainability continue to decline worldwide, losses of critical habitat and their ecosystem services have generated an urgency to understand and communicate reef response to management actions, environmental contamination, and natural disasters. Increasingly, coral reef protection and restoration programs emphasize the need for robust assessment tools for protecting high-quality waters and establishing conservation goals. Of equal importance is the need to communicate assessment results to stakeholders, beneficiaries, and the public so that environmental consequences of decisions are understood. The Biological Condition (BCG) model provides a structure to evaluate the condition of a coral reef in increments of change along a gradient of human disturbance. Communication of incremental change, regardless of direction, is important for decision makers and the public to better understand what is gained or lost depending on what actions are taken. We developed a narrative (qualitative) Biological Condition Gradient (BCG) from the consensus of a diverse expert panel to provide a framework for coral reefs in US Caribbean Territories. The model uses narrative descriptions of biological attributes for benthic organisms to evaluate reefs relative to undisturbed or minimally

* Corresponding author at: US EPA, ORD, CEMM, GEMMD, 1 Sabine Island Dr., Gulf Breeze, FL. 32561, USA.
E-mail address: raimondo.sandy@epa.gov (S. Raimondo).

1 210 Braxlo Lane, Wilmington NC 28409, USA.
2 Tetra Tech, 1810 Harris Ave., Key West, FL 33040, USA.
3 1200 Summit Blvd, Springfield, OR 97477, USA.
4 Marine Biological Laboratory, The Bell Center, 7 MBL Street, Woods Hole, MA. 02543, USA.
5 HJR Reefscaping, P.O. Box 1126, Hormigueros, Puerto Rico 00660, USA.
6 NOAA, NOS, New Orleans, LA 70130, USA.

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disturbed conditions. Using expert elicitation, narrative decision rules were proposed and deliberated to discriminate among six levels of change along a gradient of increasing anthropogenic stress. Narrative rules for each of the BCG levels are presented to facilitate the evaluation of benthic communities in coral reefs and provide specific narrative features to detect changes in coral reef condition and biological integrity. The BCG model can be used in the absence of numeric, or quantitative metrics, to evaluate actions that may encroach on coral reef ecosystems, manage endangered species habitat, and develop and implement management plans for marine protected areas, watersheds, and coastal zones. The narrative BCG model is a defensible model and communication tool that translates scientific results so the nontechnical person can understand and support both regulatory and non-regulatory water quality and natural resource programs.

1. Introduction

Coral reef ecosystems are experiencing rapid, global declines, as documented by historic mortality over multiple decades (Hughes et al. 2018; Wilkinson 2008). A significant decline in biological condition of reef benthic assemblages was observed in the tropical Western Atlantic as early as the 1970s (Gardner et al. 2003; Jackson et al. 2014; Pittman et al 2010; Ruzicka et al. 2013; Vega-Thurber et al. 2014; Weil et al. 2009, Weil et al., 2017; Wilkinson 2008). Marine coastal ecosystems, including coral reefs, are exposed to increasing loads of nutrients, sediments, pollutants, and other materials originating from terrestrial sources, which may impact coral communities acutely or through chronic exposure. These effects can be exacerbated by rising sea-surface temperatures and increased ocean acidification associated with climate change (Allemand and Osborn 2019). As coral reef ecosystems are exposed to increasing terrestrial runoff, the structural, compositional, and functional biodiversity processes are reduced, decreasing ecosystem resiliency. This state can compromise the ability of reefs to maintain essential ecosystem functions and reduces tolerance to additional human-induced disturbances (Fabricius 2005; Orlando and Yee 2016; Smith et al. 2008). Declines in coral reef condition can directly impact the ecosystem services they provide, including coastal protection, fishing, aquaculture, tourism, boating, education, cultural practices of local and indigenous peoples, and bioprospecting for novel pharmaceuticals and biochemicals (Moberg and Folke 1999; Principe et al. 2012). Coral reef ecosystem goods and services contribute billions of dollars to national, regional, and local economies that impact over 500 million people globally (van Beukering et al. 2011; Hoegh-Guldberg et al. 2019). As the condition of these valuable ecosystems declines, a scientific and systematic framework is needed to quickly evaluate coral condition and identify high- and low-quality habitats to aid future management decisions within and across political jurisdictions. A framework is presented here that provides a simplified, holistic approach using coral reef surveys and expert knowledge to determine the biological condition of coral reef sites. The approach can facilitate the evaluation and application of management actions to mitigate negative impacts of stressors and threats.

Assessing the biological condition of coral reefs requires understanding the ecological integrity of the reefs, and the stressors that threaten them. Ecological integrity is composed of all structural components and functional processes required to maintain healthy assemblages, and it includes chemical, physical, and biological integrity (Karr 2000). Biological integrity is the ability of a habitat to support and maintain a balanced, integrated, and adaptive assemblage of organisms having species composition, diversity, and functional organization comparable to that of natural habitat of the region (Frey 1977). Ecosystems with high biological integrity have a full set of elements (e.g., species diversity, stable population demographics, physical structures, etc.) and processes (e.g., biotic interactions, energy flows, metapopulation dynamics, etc.) that are expected in areas with little or no anthropogenic disturbance (Karr and Dudley 1981; Karr et al. 1986). Biological integrity is threatened by proximity and exposure to human activities that degrade physical and chemical components of the habitat (Ennis et al 2016; Fabricius 2005; Oliver et al. 2011, Oliver et al., 2018; Orlando and Yee 2016; Vega-Thurber et al. 2014). Ecological and biological integrity are important to maintain within an ecosystem because they underpin community resiliency and conservation of vulnerable species; protecting and restoring ecological and biological integrity are paramount to ensuring environmental sustainability (Frey 1977, Karr et al. 1986, Karr 2000).

The Biological Condition Gradient (BCG) is a conceptual model that relates biological condition to increasing levels of anthropogenic stress and can be used to identify biological attributes and measurable increments of change from biological condition assessments (Davies and Jackson 2006; US EPA, 2016). The BCG describes six biological condition levels ranging from undisturbed or natural (BCG level 1) to highly disturbed or degraded conditions (BCG level 6) (Fig. 1). As demonstrated in the present study and noted elsewhere (Jackson et al. 2014, Pandolfi et al. 2003, Pandolfi et al., 2005), undisturbed or natural reefs have largely disappeared from the Caribbean, impressing the urgency for tools such as BCG models to assist natural resource managers and stakeholders evaluate changes in coral reefs. This framework was originally implemented in freshwater systems in the USA to support state biological assessment and criteria programs (Davies and Jackson 2006). Santavy et al. (2016) proposed an adaptation of the BCG framework to apply to reef corals in the Caribbean as a proof of concept. Here, we expand on that work to include narrative decision rules that natural resource managers can use to guide assessments of reef condition, identify high quality waters, set restoration targets, and improve communication with the public on predicted consequences of management decisions. The objective of this work is to provide user-friendly framework for managers to use in scenarios where quantitative data on reef attributes, which require resource intensive reef surveys to obtain, are lacking. We demonstrate the narrative BCG model as a tool to communicate management decisions to stakeholders and the public who have vested interests in water quality improvements, selecting restoration sites, tracking recovery progress, and developing biological criteria (biocriteria). We demonstrate several applications to inform management goals and discuss its use in conjunction with two companion models: a quantitative coral and benthos BCG (Santavy et al. 2022) and a coral reef fish BCG (Bradley et al. 2020).

2. Materials and methods

There are five iterative steps to develop and calibrate a BCG narrative model (US EPA, 2016): 1) assemble and organize bioassessment data, 2) conduct preliminary data analysis and preparation, 3) convene expert panel on coral reef organisms and habitats, 4) assemble panel ratings of site conditions to develop BCG narrative model through a process of expert elicitation and consensus, and 5) translate site ratings and rationale into narrative model. The model is tested, adjusted, and recalibrated to reflect the expert consensus. For our study, data assembly, analysis, and preparation (steps 1 and 2) required evaluation and examination of selected sites in Puerto Rico to determine whether the full range of biological conditions were represented by high quality data. Next, expert panelists were selected to represent a breadth of expertise and experience in field assessments, marine ecology, biology, and taxonomy. They were oriented to BCG concepts and methods (step 3), rated condition of coral reef sites, identified critical biological elements, and stated rationale for their ratings to develop descriptive narrative traits (e.g., % coral cover) for each BCG condition level (step 4). Site ratings and rationale were translated into the narrative model with decision rules that were confirmed, adjusted, and recalibrated as necessary (step 5). Any step of the process may be revisited if the model performance is not satisfactory, or deficiencies are identified. A complimentary numeric BCG model for Caribbean coral was also derived from this process and presented in Santavy et al. (2022).

Detailed notes, summaries, and worksheets from the workshops and webinars that were held to develop the current narrative benthic BCG model, the numeric benthic BCG model (Santavy et al. 2022), and the marine fish BCG (Bradley et al. 2020) are presented in US EPA (2021). Workshop and webinar processes are provided in this technical report to support transparency in the expert panel discussions that resulted in the development of the narrative rules, as well as provide the information that comprised the basis of the present model to future researchers interested in updating the models as new sites and data become available. We advise future updates to this model be based on discussions from experts with the equivalent levels of experience as the panelists listed in Supplemental B.

2.1. Step 1: Assemble and organize bioassessment data

Step 1 required assembling and organizing appropriate bioassessment databases from coral reef studies for the expert panel to examine. Data for the benthic BCG narrative rules were obtained from surveys conducted along the south coast of Puerto Rico in 2010 and 2011. Metrics calculated and provided to the expert panel included scleractinian coral condition and abundance, sponge, and gorgonian metrics (Supplemental Information A) (Fisher et al. 2019; Santavy et al. 2012, Santavy et al., 2013; Bradley et al. 2014; data on EPA's Environmental Dataset Gateway, US EPA EDG 2018). Although the surveys were not originally designed for BCG calibration, they met the criteria required for calibration of datasets for model development (US EPA, 2016). The sites within the dataset did not include the highest quality reefs expected for BCG level 1, but they included reefs that ranged from good to very poor condition. Experts attributed the absence of BCG level 1 and the very low number of BCG level 2 sites to the scarcity of high-quality reefs which might not exist throughout the Caribbean (Jackson et al. 2014) rather than a deficiency in the dataset. The process for defining BCG level 1 characteristics in the absence of natural sites in the dataset is described below under Step 4.

2.2. Step 2: Conduct preliminary data analysis and data preparation

Data used for the expert panel deliberations are described in Supplemental Information A. Briefly, colony surface area (CSA) represented all skeletal surface structures (cm^2) for a single colony including its top, sides, branches, and other skeletal features, but excluded basal areas attached to the substrate. Live colony surface area (LCSA) was tissue covering the CSA or skeletal surface area (cm^2) (Fisher et al. 2007, Fisher et al., 2019; Santavy et al. 2012). All colonies were $\geq$ 10 cm maximum diameter. When calculating colony surface areas, a species-specific morphology factor (Supplemental Information A, Table A1) was used to estimate the three-dimensional exterior colony surface area and reported as average CSA or LCSA by species (average cm^2 of skeleton or tissue area/colony). Colony surface area metrics (CSA and LCSA) were not directly comparable to planar percent coral cover (%CC) standardized by species that is reported from many past studies (Hill and Wilkinson 2004; Jokiel et al. 2015). The %CC estimates total live tissue from all colonies viewed in two dimensions as observed from above the colonies and excludes surface area on colony sides from complex morphologies as branching, foliose, or non-encrusting forms (Fisher et al. 2007, Fisher et al., 2019; Oliver et al. 2018). To provide experts with a comparable coral cover metric to %CC, a 2-dimensional planar (2D) coral cover was estimated using maximum colony diameters to calculate planar area of each colony and summed by species.

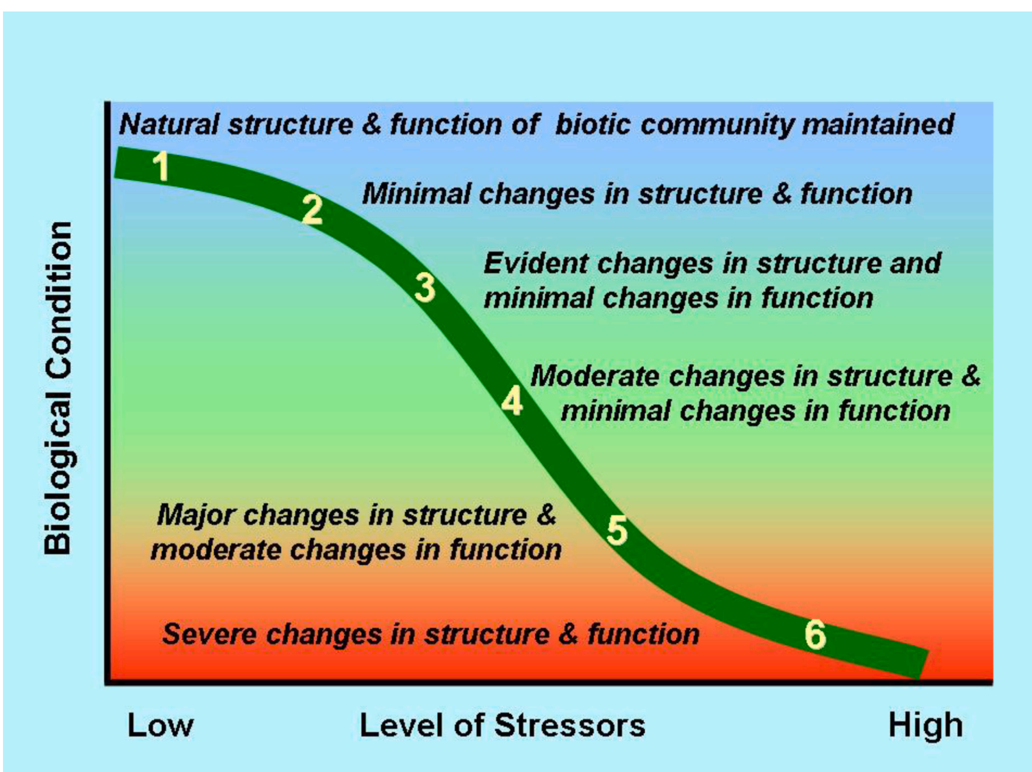

Fig. 1. Conceptual model of the BCG with biological condition on the ordinate axis and the level of exposure to anthropogenic stressors on the abscissa axis (adapted from Davies and Jackson 2006).

Coral total surface area (TSA) and total live surface area (TLSA) represented the sum of CSA and LCSA, respectively, for all colonies in a 25 m^2 transect averaged per m^2 of substrate reported by species. Additional coral metrics were percent coral colony mortality (% M), colony density, and taxa richness. Physical features documented for each site were maximum and minimum depth, coarse rugosity (Risk 1972), substrate type (hard, soft, rubble, sand), *Diadema antillarum* (sea urchin) abundance, fish species richness, distance of reef from nearest shore and shelf, density of boring clionid sponges, and prevalence bleaching or disease by coral species (Santavy et al. 2012). It should be noted that values of these metrics were used as reference material for the expert panel and are not included as part of the BCG model presented here. Formal association of quantitative metric values with BCG levels is presented in Santavy et al (2022).

2.3. Step 3: Convene an expert panel

The expert panel was comprised of 23 scientists with extensive experience and expertise in Caribbean and western Atlantic coral reefs (Supplemental Information B). Panel members had expertise across topics ranging from taxonomic groups (e.g., scleractinian corals, fishes, sponges, gorgonians, algae, seagrasses, and other macroinvertebrates), community structure, organism condition, ecosystem function, and ecosystem connectivity. Panelists were selected to represent territorial governments from Puerto Rico and US Virgin Islands (2 panelists), federal (8 panelists), academic institutions (9 panelists), Non-Governmental Organizations (NGOs; 3 panelists), and the private sector (1 panelist) to minimize internal bias (US EPA, 2016) and included a range of experience (5 to 50 + years) working with coral reefs. In total, the panel represented over 600 years of combined experience working with Caribbean coral.

The panel convened during three workshops in Puerto Rico and numerous webinars to develop, review, and refine the model. The primary objectives of the first workshop were to introduce the expert panel to the objectives and concepts of the BCG, develop a generalized coral reef condition framework, and provide instructions for developing a BCG model. During the second workshop, experts developed consensus on a reef habitat classification system, evaluate species sensitivity and tolerance to anthropogenic stressors, and evaluate the biological condition of coral assemblages for sites. During the third workshop and subsequent webinars, experts deliberated and developed the narrative coral BCG model.

During the first workshop and prior to an introduction to the BCG concept, experts developed a general framework that defined biological condition of reef sites ranging from excellent to poor. Each expert evaluated underwater photographs and videos from 12 survey sites, selected to represent a range from very good to poor condition (Bradley et al. 2014; Santavy et al. 2016). Experts individually described and rationalized the characteristics they considered most important for classifying reef condition. These characteristics included structural and functional elements of different assemblages, ecological processes, and evident changes in coral reef condition. Group discussions and deliberations followed when experts shared their insights, logic, and knowledge to develop a consensus description of structural composition and ecological processes characteristic for general condition categories (Supplemental Information C, Table C1). Next, workshop facilitators oriented the experts to the BCG concepts, terms, data descriptions, methods, worksheets, and process for developing a narrative model.

Habitat classification was required to establish reference conditions and benchmarks for biological assessments. The classification defined environmental characteristics of a functioning, natural reef system to discriminate between natural patterns of change from alterations caused by anthropogenic stress. Coral reef communities are zoned by differences in depth, wave energy, temperature, and light (Stoddard 1973; Zitello et al. 2009). The panel selected a hierarchical classification scheme (Costa et al. 2009, Costa et al., 2013) to group sites by reef types, geographic zones, and geomorphological structures (Table 1). Additionally, reef zones, geology, sea level change, sediment exposure, and decadal temperature anomalies are important determinants of expected species composition (Costa et al. 2009, Costa et al., 2013; Hubbard 1997; Hubbard et al. 2009; Stanley 2003; Zitello et al. 2009). To ensure consistency across similar sites, only reefs classified as *fore reef zone* (i.e., area along seaward edge of reef crest that slopes into deeper water on a barrier or fringing reef; Costa et al. 2013) were used for this model. Reefs were also fore reef if they were non-emergent reef crests but still had a seaward-facing slope that was significantly greater than the slope of the bank/shelf. Fore reefs were further divided into two zones: one dominated by *Orbicella* species complex or else colonized hard bottom with gorgonian plains (Williams et al. 2015). For the purpose of model development, only the zone dominated by *Orbicella* species complex was used.

Ten BCG attributes are generally defined in the BCG framework for all environments, and they incorporate taxa sensitivity, organism condition, and ecosystem functions (Davies and Jackson 2006; US EPA, 2016) (Table 2). Attributes are responsive to taxa structure and compositional changes when exposed to major anthropogenic stressors. The panel assigned each Caribbean coral species to the first six attributes (as Roman numerals) as the information for attributes VII-X was not fully developed for coral reef assemblages (BCG attributes VII and VIII) or not applicable at the spatial scale of coral reefs (BCG attributes IX and X). Each species was assigned an attribute level I-V based on their sensitivity and tolerance to elevated sea water temperature and sensitivity to sediment. This was conducted using studies published at the time the workshops were held (e.g., Bak 1978; Carpenter et al. 2008; Dodge and Vaisnys 1977; Erftemeijer et al. 2012; Fitt et al., 2001) and the collective experiences of the expert panel in accordance with standard BCG model development guidelines (US EPA, 2016, US EPA, 2021). Sediment sensitivity served as a surrogate for land-based sources of pollutant runoff. Attribute VI was assigned to non-native or invasive species. If a species could not be confidently assigned a BCG attribute level, no assignment was made.

2.4. Step 4: Rate condition of sites through expert elicitation and consensus

The panelists individually evaluated the biological condition of sites based on the general BCG descriptions previously defined (Davies and Jackson 2006; Table 3) and assigned a BCG condition level (1–6). Ideally for BCG model development, a minimum of 20 sites would be assigned to each BCG level scored by a minimum of five experts (Gerritsen et al. 2017). The experts confirmed the site was a good candidate for being in

Table 1
Benthic habitat classification that defines habitat classes (adapted from Costa et al. 2013).

Reef type	Reef geographic zones	Reef geomorphological structures
Barrier Reef	Lagoon Back reef Reef flat Reef crest Fore reef Bank/shelf	Coral reef and hard bottom Aggregate reef Aggregated patch reef Individual patch reef Pavement Pavement with sand channels
Fringing Reef	Reef flat Reef crest Fore reef Bank/shelf Bank/shelf escarpment	Reef rubble Scattered coral and rock Bedrock Spur and groove Mid fore reef terraces
Non-Emergent Reef Crest	Bank/shelf (shallow) Fore reef Bank/shelf (deep) Bank/shelf escarpment	

Table 2
Generic descriptions of BCG ecological attributes used to assign coral taxa into BCG attribute levels I-VI (adapted from US EPA, 2016).

Number	Name	Description
I	Historically documented, sensitive, long-lived, or regionally endemic taxa	Taxa known to have been supported by historical, museum, or archeological records, or taxa with restricted distribution (restricted to a locale as opposed to a region), often for unique life-history requirements
II	Highly sensitive taxa	Taxa highly sensitive to pollution or anthropogenic disturbance; occur in low numbers, and many are specialists for habitats and food type; first to disappear with disturbance or pollution
III	Intermediate sensitive taxa	Common taxa ubiquitous and abundant in relatively undisturbed conditions but sensitive to anthropogenic disturbance/ pollution; have a broader range of tolerance than most taxa
IV	Intermediate tolerant taxa	Ubiquitous and common taxa found at most conditions, from undisturbed to highly stressed sites; broadly tolerant and decline under extreme conditions
V	Tolerant taxa	Taxa uncommon and low abundance in undisturbed conditions but increase in abundance in disturbed sites; opportunistic species can exploit resources in disturbed sites; last survivors
VI	Non-native or intentionally introduced species	Any species not native to ecosystem
VII	Organism condition	Anomalies of organisms; indicators of individual health (e.g., deformities, lesions, tumors, loss of tissue)
VIII	Ecosystem function	Processes performed by ecosystems: primary and secondary production, respiration, nutrient cycling, decomposition, proportion/ dominance, and dominant functions components of ecosystem
IX	Spatial and temporal extent of detrimental effects	Spatial and temporal extent of cumulative adverse effects of stressors
X	Ecosystem connectance	Access or linkage (space/time) to materials, locations, and conditions required for maintenance of interacting populations of aquatic life; opposite of fragmentation

a fore reef zone by viewing Google Maps™ aerial photos (accessed 2012 to 2016). Underwater videos and photos taken during the surveys at each site were viewed by the experts for evidence of recent or past Orbicellid growth or skeletal remains. If the experts did not confirm a site was a legitimate fore reef site, they did not evaluate it. Each expert assigned a BCG level with a justification for their assignment and described the traits with the greatest weights for their decisions for every site. Occasionally, experts confirmed the level included a plus (+) or (−) if an expert determined the condition of a site was between two BCG levels. For example, if a site was an approximate BCG level 3, an expert could give it a score of '3+' if they perceived the traits tended towards BCG level 2, and a '3−' if they perceived the traits tended towards BCG level 4. Once individual expert ratings and associated rationales were submitted, facilitated panel discussions followed to discuss ratings from all the experts and develop a collective rationale. Panelists could change their original rating and rationale if compelled by discussion among their peers and adjusted rating was used. This iterative process served to minimize individual bias and develop group consensus on which sites represented each BCG level.

Experts' ratings and justifications were used to qualitatively describe each BCG level. A median score was assigned to each site calculated from all the experts' ratings. Since experts could assign intermediate levels (i.e., 3 + rating vs. 3−) and the distinction between a 3− and 4 + is subjective, such scores were valued as $^{1}/_{3}$ of a BCG level. Recorded comments were consolidated into draft narrative decision rules for each BCG condition level by the facilitators. The experts' logic and language used to describe each site were translated into scientific traits, metrics, or characteristics to be consistent across experts, attributes, and condition levels. Narrative rules were refined and clarified as more sites were evaluated and discussed. While experts were provided numeric values of metrics derived in Step 2, metric values were used as supplemental information during these discussions and were not integrated as part of the narrative rules. These discussions documented iterations of panel discussions that referenced expert logic to underpin the model for testing and re-calibration as necessary.

Since natural, undisturbed conditions were not found at the sites evaluated, historic data and expert knowledge from the panel were used to generate a narrative characterization of BCG level 1 to describe the best possible conditions or full biological integrity. Historical ecology was extracted from McClenachan et al. (2015) and historical conditions and descriptive studies of precolonial distributions of species and physical habitat structures were obtained from Jackson et al. (2014). Experts collectively supplemented these sources with their extensive field experience and ecological knowledge of the region, natural classification of assemblages, and historical accounts of habitats and assemblages. While some studies suggest that current coral reef researchers may have a poor understanding of what natural Caribbean reefs should be like (Jackson et al. 2011, Jackson et al., 2014), many of the panelists had first-hand experience of Caribbean coral reefs predating the 1970 s. The combined contributions of literature and personal experience were deliberated iteratively by the panel to derive reef characteristics that categorize BCG Level 1 and represents a collective expert agreement. The final agreement on characteristics of BCG level 1 were then codified by the panel to prevent shifting baselines in perception of natural Caribbean reefs. Additionally, the habitat classification used by the panel aided in defining environmental characteristics of a functioning, natural reef system to discriminate between natural patterns of change associated with spatial heterogeneity from those caused by anthropogenic stress. Since all BCG models functionally rely on level 1 conditions as a starting point, expert agreement on these characteristics was a critical component of the present model.

2.5. Step 5: Translate ratings and logic into narrative model, test and adjust decision rules to replicate expert consensus

The site ratings and rationales were translated into decision rules to form a narrative model that was evaluated, adjusted, and recalibrated to improve the model's ability to replicate the experts' interpretation. Performance of the narrative coral BCG model was continuously evaluated as part of the rule develop, revisiting previously discussed sites as additional sites were rated and examined to ensure consistency throughout the rule development process. This allowed the expert panel to compare rationales expressed across sites and ensure sites evaluated in the later portion of the develop process was consistent with those evaluated in the beginning stages of this process. A final verification exercise performed by the expert panel occurred when final narrative decision rules were agreed upon to ensure all sites used in model development adhered to the final set of rules for each BCG level.

The BCG decision model functions as a logical cascade reviewing rules for BCG level 1 first and proceeding to each level until decision rules are met or all rejected, to assign the site to BCG level 6 (US EPA, 2016; Gerritsen et al. 2017). After experts agreed to consensus decision rules, each site was again tested against the rules for BCG level 1. If a required rule or minimum number of rules were not met, the site failed that level. Next, the site was evaluated against BCG level 2 rules in the manner described above, etc. Alternate or combined rules required that

Table 3
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 preserved; ecosystem function preserved within the range of natural variability. BCG Level 1 represents biological conditions as existed (or still exist) in absence of measurable effects of stressors; provides basis for comparison to next five levels.
Level 2	Minimal changes in structure of biotic community and minimal changes in ecosystem function	Virtually all native taxa maintained with some changes in biomass and/or abundance; ecosystem functions fully maintained within range of natural variability. Level 2 represents earliest changes in densities, species composition, and biomass that occur during slight increase in stressors (e.g., increased temperatures or nutrients).
Level 3	Evident changes in structure of biotic community and minimal changes in ecosystem function	Evident changes in structure of biotic community and minimal changes in ecosystem function. Some changes in structure by loss of some rare native taxa; shifts in relative abundance of taxa, but intermediate sensitive taxa common and abundant; ecosystem functions fully maintained through redundant attributes of ecosystem. Level 3 represents readily observable changes that occurs to organic enrichment or increased temperature.
Level 4	Moderate changes in structure of biotic community with minimal changes in ecosystem function	Moderate changes in structure by replacement of some sensitive-ubiquitous taxa by more tolerant taxa; reproducing populations of some sensitive taxa maintained; overall balanced distribution of all expected major groups; ecosystem functions largely maintained through redundant attributes.
Level 5	Major changes in structure of biotic community and moderate changes in ecosystem function	Sensitive taxa 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 build-up or export of unused materials. Changes in ecosystem function (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 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 often poor; ecosystem functions severely altered. Level 6 systems taxonomically depauperate (low diversity or reduced number of organisms) compared to other levels.

they must be combined with Boolean operator '*and*' (i.e., all must be true) or with Boolean operator '*or*' (i.e., only one must be true). Any decision rule could be reconsidered by the panel if deficiencies or improvements were required. Since the qualitative decision rules are inherently subjective, this final verification of all sites used to develop the model was intended to confirm concurrence among all expert panelists and is not considered a true model validation.

3. Results

During the first workshop, experts conceptualized a coral reef condition framework from site videos to evaluate important reef characteristics and define data requirements to assess the biological condition of coral reefs. Prior to introduction to the BCG framework, the experts formulated expectations aimed at four condition categories: excellent to very good, good, fair, and poor. This was conducted by employing coral taxa attributes and biological characteristics, using the data collected in Step 2 as Supporting information, to align with important structural and functional characteristics. Eight elements were identified to describe changing physical and biological conditions among these four condition categories: 1) reef physical structure representing topographical heterogeneity, complexity of the reef surface; 2) coral species, morphology, size, and population demographics; 3) sponge and gorgonian morphology, size, and potential for habitat provision; 4) coral condition reported as live tissue present and extent of disease, bleaching, and tumors; 5) fish abundance, biomass and trophic interactions; 6) presence of charismatic megafauna as turtles, large fish, and dolphins; 7) selected invertebrates *Diadema antillarum*, conchs, lobsters, and crabs; and 8) calcareous, crustose coralline, filamentous, fleshy, and turf algae; and submerged aquatic vegetation.

3.1. Assignment of taxa to BCG attribute levels

Each taxon was evaluated for sensitivity and tolerance to anthropogenic stressors, rarity, and endemism (Davies and Jackson 2006; US EPA, 2016). Experts converged on terminology that reflected generic attribute definitions (Table 2) and concurred that abundance, dominance, frequency, vitality, and natural variations or cycles were useful traits for identifying responsive species. Coral experts agreed that elevated sea temperature and land-based sources of pollution (e.g., sedimentation, chemical contaminants, nutrients) present the most serious threats for Caribbean scleractinian corals and chose to evaluate each taxon for each stressor separately.

The experts assigned 48 scleractinian and hydrozoan hard coral species of the Western Atlantic to BCG attributes II–V (Table 4). No species were assigned to BCG attribute I (endemic and rare). BCG attributes II through V were assigned to species with increasing levels of tolerance to stress, with BCG attribute II highly sensitive and BCG attribute V highly tolerant. Only *Isophyllia rigida* and *Isophyllia sinuosa* were assigned to attribute II indicating high sensitivity to both heat and sediment stress. Approximately 19% of species were assigned to BCG attribute III for medium sediment tolerance that included the threatened species *Acropora cervicornis* and *Dendrogyra cylindrus* as defined in US Endangered Species Act (ESA). *Agaricia lamarcki* and *Madracis decactis*

Table 4
Sensitivity and tolerance of coral species to sediment and elevated sea temperature assigned to BCG attributes I-V by expert panel. I = Rare, long-lived or endemic taxa; II = Highly sensitive taxa; III = moderately sensitive taxa; IV = intermediate, broadly tolerant taxa; V =taxa tolerant to disturbance and pollution; VI = nonnative taxa; X =insufficient information for panel to assign level; blanks indicate taxa not identified.

BCG Attribute Level	Coral Scientific Name	Sediment stress	Heat Tolerance
II	*Isophyllia rigida*	II	II
II	*Isophyllia sinuosa*	II	II
III	*Acropora cervicornis*	III	III
III	*Agaricia lamarcki*	III	II
III	*Colpophyllia natans*	III	III
III	*Dendrogyra cylindrus*	III - IV	III
III	*Diploria labyrinthiformis*	III	III
III	*Eusmilia fastigiata*	III	III
III	*Helioseris cucullata*	III	III
III	*Madracis decactis*	II - IV	IV
III	*Millepora complanata*	III	II
IV	*Acropora palmata*	IV	III
IV	*Acropora prolifera*	IV	III
IV	*Agaricia agaricites*	IV	II
IV	*Agaricia humilis*	IV	II
IV	*Cladocora arbuscula*	IV	IV
IV	*Dichocoenia stokesii*	IV	III
IV	*Madracis auretenr*[1]	IV	III
IV	*Meandrina jacksoni*[2]	IV	III
IV	*Meandrina meandrites*	IV	III
IV	*Mussa angulosa*	IV	II
IV	*Mycetophyllia aliciae*	IV	III
IV	*Mycetophyllia ferox*	IV	II - III
IV	*Orbicella annularis*	IV	II
IV	*Orbicella faveolata*	IV	II
IV	*Orbicella franksi*	IV	II
IV	*Porites furcata*	IV	IV - V
IV	*Porites porites*	IV	IV
IV	*Scolymia cubensis*	IV	IV
IV	*Scolymia lacera*	IV	IV
V	*Favia fragum*	V	IV
V	*Manicina areolata*	V	V
V	*Millepora alcicornis*	V	II
V	*Montastraea cavernosa*	V	IV - V
V	*Oculina diffusa*	V	IV
V	*Porites astreoides*	V	V
V	*Porites divaricata*	V	IV
V	*Pseudodiploria clivosa*	V	IV
V	*Pseudodiploria strigosa*	V	IV
V	*Siderastrea radians*	V	V
V	*Siderastrea siderea*	V	IV
V	*Solenastrea bournoni*	V	IV
V	*Stephanocoenia intersepta*	V	IV
VI	*Tubastrea coccinea*		
x	*Agaricia fragilis*	X	X
x	*Millepora squarrosa*	X	II
x	*Mycetophyllia daniana*	X	X
x	*Mycetophyllia lamarckiana*	X	X
x	*Porites branneri*	X	

were assigned to attribute III for sediment tolerance, but the former had attribute II indicating a lower heat tolerance and the latter had attribute VI indicating a higher heat tolerance respectively. Experts defined sediment tolerance attribute levels more broadly ranging from III to IV for *Dendrogyra cylindrus* and II-IV for *Madracis decactis*. Approximately 38% of the species were assigned to attribute IV for tolerance to sediment stress including the US ESA threatened species: *Acropora palmata, Mycetophyllia ferox, Orbicella annularis, Orbicella faveolata,* and *Orbicella franksi.* While most of the ESA species (72% attribute IV sediment tolerance) were considered more heat sensitive and assigned attribute level II or III for temperature tolerance. Ten percent of taxa were not assigned an attribute level due to high uncertainty, dissenting, or no opinion on their stressor responses by expert. The only non-native species was *Tubastrea coccinea.*

3.2. Develop narrative decision rules and model validation

The decision logic was articulated as critical biological components that experts considered to rate the site, such traits included: taxa richness, diversity, population density, presence of reef-building species, tolerant/sensitive taxa, organism condition, size-class structure, and recent or old mortality. Experts were asked to express what shifts in community structure and function might change their rating to another BCG level to delineate ecologically meaningful decision rules. No undisturbed or minimally disturbed sites were rated, so BCG level 1 was defined narratively using historical literature and expert knowledge as provided in detail in Supplemental Information D. The experts determined how the rules for each level were to be applied selecting that: (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 (US EPA, 2016).

The decision rules for the narrative coral BCG are in Table 5 and representative reefs for each BCG level are demonstrated in Fig. 2. Generally, a pattern of decreasing %CC was accompanied by higher percentages of tissue loss on individual coral colonies with increasing BCG levels 4 to 6. Additional rules included decrease in reef rugosity, increased mortality of coral colonies and disease prevalence. Algal composition changed with increased stress. In BCG levels 1 through 3, crustose coralline algae were more abundant, but as biological conditions degraded, turf and fleshy algae increased. With increased degradation, the total number of narrative rules for each subsequent BCG condition level decreased until BCG level 6 was defined by the absence of most assemblages found in better BCG condition levels.

4. Applications and case studies

The narrative BCG model uses nontechnical language to qualitatively inform biological condition goals for regulatory and non-regulatory water quality and natural resource programs. While numeric BCG models, such as those presented in Bradley et al (2020) and Santavy et al (2022), are valuable for linking numeric endpoints to BCG levels quantitatively, narrative BCG models have great utility across a range of applications. Common narrative language can be used to describe and compare habitat condition for coral reef communities for planning and protection of Marine Protected Areas (i.e., protection of high-quality waters, national parks, etc.), managing resources for sustainable fisheries and tourism, and making best management decisions for adjacent watersheds and coastal zones (Bradley et al. 2009). Applying BCG narrative language facilitates better understanding while reporting on water body condition, evaluating restoration actions, and planning for wastewater and stormwater discharges. As demonstrated in the following case studies, the narrative BCG model can be used to establish biocriteria for coral reef ecosystems (Case Study 1), develop impact assessments to identify high quality reefs and identify ESA-listed species at high risk from human activities (Case Study 2), and provide scientifically based thresholds while improving communication among government and public stakeholders (Paul et al. 2020) (Case Study 3).

As with all models, application of the narrative BCG model should include a discussion of uncertainties. A primary source of uncertainty in the application of narrative BCG is the subjectivity that is inherent in terms such as “many”, “few”, “large”, etc. Use of subjective language is standard practice of all narrative BCGs (Bradley et al. 2020; Davies and Jackson 2006; Hausmann et al. 2016; Shumchenia et al. 2015; USEPA 2016) and is used to describe relative condition of reefs along a spectrum. While different end users may have slightly different interpretations of these terms, an uncertainty analysis and discussion should clarify the interpretation of these terms by the user. The iterative deliberations of the expert panel resulted in multiple rules for each BCG level and included terms such as “and” and “or” within the set of rules

Table 5
Benthic BCG narrative rules using coral metrics for model development in fore reef habitats.

Assemblage or Element	Narrative Description
BCG Level 1 Natural or native condition	
Scleractinian Corals	> 60% live cover of coral in fore reef habitat High majority (>98%) of scleractinians colonies healthy, no signs of disease or stress (discolorations, bleaching; large injuries). Low prevalence of bleached colonies may be present temporarily (Summer –Fall). High species diversity (>25 species, or 50–70% max. taxa for region). Large Reef-Building Corals species (LRBC) abundant with large and medium colony size, healthy colonies, and a high proportion of the total live coral cover (EW list is: *Acropora* spp., *Orbicella* spp., *Pseudodiploria* spp., *Siderastrea* sp., *Diploria* sp., *Undaria* spp., *Porites* spp. Presence of several colonies of "rare" species such as *Dendrogyra cylindrus*, *Helioceris cucullata, Scolymia cubensis*, *Isophyllia* spp., and *E. fastigiata.* Most colonies within each species population much larger than minimum reproductive size, indicating continuous sexual and sustainable reproductive output. Abundance of smaller colonies and juveniles indicates successful settlement and survivorship during the early larval stages with high mortality stages. Presence of recruits (<4cm) and abundant juvenile colony sizes (≥4cm and < 10 cm).
Spatial Heterogeneity	Complex physical structure (3D high rugosity framework) of aragonite branching, columnar, massive domes, and plates of mostly live corals. Provides habitat, refuge, and resources to a high diversity of organisms (e.g., invertebrates, fish, sea turtles, etc.).
Macro Invertebrates	Large, healthy, and abundant colonies of hydrocorals. Moderate cover of zoanthids including healthy *Palythoa caribbaeorum* (shallow exposed areas, can dominate consolidated substrate areas, presence of other individual and colonial anemones. Moderate densities of the black sea urchin *Diadema*, presence of other urchin species and echinoderms (sea stars, sea cucumbers, etc.). Abundant and diverse crustacean populations (spider crabs, stone crabs, lobsters, snapping shrimp, etc.), colorful polychaetes, and mollusks.
Algae	Crustose coralline algae (CCA) abundant with low to moderate cover and wide distribution. Low abundance (cover) and diversity of macro-algae and turf algae. Populations grazed by the abundant herbivorous fish and sea-urchins.
Octocorals	Large and abundance colonies, high species diversity of sea fans and branching colonies, provides structural complexity. Low to moderate abundance of encrusting species.
Sponges	Low to moderate abundance, high species diversity of medium to large healthy barrel, branching, tube, and massive sponges. Low to moderate cover of crustose, endolithic species (e.g., Clionids).
Physical Environment	Favorable environmental conditions over time – low variability in temperature, salinity, pH, good water circulation, high water transparency and low sedimentation.
BCG Level 2 Minimally disturbed	
Scleractinian Corals	> 45% live cover of coral in fore reef habitat Minimal recent mortality in LRBC include the following species: *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*. Normal frequency distribution of colony sizes within each species size range to include large, medium, juvenile 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 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.
Spatial Heterogeneity	High rugosity resulting from large living coral colonies, producing spatial and topographical complexity
Macro Invertebrates	*Diadema* abundant; reef macroinvertebrates (e.g., lobsters, crabs) common and abundant. Low levels of invertebrate coral predators (*Coralliophylia* spp.*, Hermodice* sp.)
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
Physical Environment	Mostly high clarity, low particulates
BCG Level 3 Good	
Scleractinian Corals	> 25% live cover of coral in fore reef habitat Higher percentage of tissue loss with signs of recent mortality especially on large reef-building genera (*Orbicella, Pseudodiploria, Colpophyllia, Acropora, Dendrogyra*) but is still overall lower than Level BCG 1–2. 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)
Spatial Heterogeneity	Moderate to high rugosity or reef structure resulting from large living reef-forming and dead coral colonies, producing spatial complexity (or topographical heterogeneity)
Macro Invertebrates	*Diadema* present Reef macroinvertebrates (e.g., lobsters, octopus, conch) present
Algae	Minimal presence of fleshy, filamentous, and cyanobacterial algal cover Crustose coralline and tuft algae present
Sponges	Phototrophic sponges present Low cover and abundance of Clionid boring sponges
Physical Environment	Mostly good to moderate water quality
BCG Level 4 Fair	
Scleractinian Corals	> 15% live cover of coral in fore reef habitat Moderate amount of recent mortality on reef-building genera (*Orbicella, Pseudodiploria, Colpophyllia, Acropora, Dendrogyra)* Colony size distribution: large colonies may be absent, primarily medium and small colonies Species composition and diversity: sensitive species may be absent *(Agaricia, Mycetophyllia, Colpophyllia),* more tolerant species present *(Montastraea cavernosa, Siderastrea siderea, Porites astreoides);* some reef-building corals present but not dominant *(*primarily *Orbicella)* Moderate levels of disease and potential bleaching on corals
Spatial Heterogeneity	Rugosity due to old mostly dead coral structure
Macro-Invertebrates	*Palythoa* may be present, sea fans and branching gorgonians present with disease
Algae	Moderate to high amount of fleshy, filamentous and cyanobacterial algal cover
Sponges	Moderate cover and abundance of Clionid boring sponges
Physical Environment	Water quality and clarity may be poor
BCG Level 5 Poor degraded	
Scleractinian Corals	> 5% live cover of coral in fore reef habitat Higher mortality of individual colonies is evident, or remnant colonies or reef structure bioeroded, low amount of tissue remains on colonies
Spatial Heterogeneity	Low rugosity, that which is present may be dead coral structure
Macro-Invertebrates	*Palythoa* predominant, more gorgonians replacing coral colonies
Algae	Coral cover replaced by fleshy, filamentous and cyanobacterial algae
Sponges	

(*continued on next page*)

Table 5 (*continued*)

Assemblage or Element	Narrative Description
	Highest presence of Clionid boring sponges
	Non-phototrophic sponges predominant
Physical Environment	Water quality and clarity mostly poor
BCG Level 6 Very Poor	
	Does not meet rules for BCG Level 5

for each BCG level to reduce the weight of subjective interpretation of any single rule. To account for natural variation in heterogenous distribution reef species, the BCG also allows a user to rate sites using '+' and '−', as described in the methods, to account for sites that do not fall squarely within a single level. There is a degree of subjectivity associated with this approach as one model user may identify a site as '2−' while another user may designate the same site as a '3+'. However, the functionality of the model to identify a relative condition of coral reef still retains its power to separate severely degraded sites (e.g., levels 5–6) from sites that still retain some ecological integrity (e.g., levels 2–3), even considering such subjectivity.

4.1. Case study 1: BCG condition levels as biocriteria in US clean water Act (CWA)

Biocriteria are described as numeric values or narrative descriptions based on the composition, abundance, and distribution of species at reference sites and used to describe waterbody condition protective of natural biotic life uses or biological integrity, as required by the CWA (Bradley et al. 2010). Biocriteria are developed for aquatic environments in 51 US states and territories (including Puerto Rico and the US Virgin Islands), and multiple tribes that use narrative or numeric approaches (US EPA WQC BC. 2017a). To date, 15 states have adopted narrative biocriteria into their water quality standards (WQS), and ten have used narrative biocriteria statements supplemented with quantitative procedures. Only five states have adopted numeric biocriteria into their WQS (US EPA WQC BC. 2017b). The narrative benthic BCG framework can be used to relate chemical, physical, and biological assessments and develop criteria for a more integrated, comprehensive evaluation of the condition of a waterbody associated with coral reefs. To date, biocriteria have been used in the USA to: develop WQS; support listing of impaired waters under the CWA (45 states); support antidegradation policies (15 states); refine aquatic life uses (22 states); perform water condition assessments (43 states); perform non-point source assessments (38 states); evaluate best management practices (BMP) (30 states); and develop restoration goals (28 states) (US EPA WQC BC. 2017c).

The narrative descriptions of the BCG levels presented define specific biota and habitat features expected for different condition qualities of a coral reef and can be applied directly as narrative biocriteria. For example, the BCG levels defined here can help describe aquatic life uses and guide potential restoration goals of coral reefs. Coral reef biocriteria have been the basis for decisions for issuing permits for land and water use by municipalities, developers, and other stakeholders to balance ecosystem goods and services that coral reefs provide for human use and well-being with other interests of stakeholders (Santavy et al. 2021).

4.2. Case Study 2: Use of the BCG for environmental impact assessment

In partnership with the US EPA, Puerto Rico developed an environmental impact statement for a proposed offshore liquified natural gas (LNG) facility in Jobos Bay National Estuarine Research Reserve, Puerto Rico during 2013. The facility would convert natural gas from a liquid to a gaseous state and transfer it via pipeline to an onshore power plant. A permit was requested as required by law to construct a pipeline that would transport natural gas to an onshore power plant, with the original proposal placing the pipeline through the most direct, shortest route from land to the docking station. The impact assessment was conducted under the US National Environmental Protection Act (NEPA) to evaluate placement of the gas pipeline in the vicinity of sensitive coral reefs.

To facilitate this assessment, the narrative benthic BCG model was used to advise pipeline routing to protect ecologically important and sensitive reefs that contained threatened and endangered coral species in Puerto Rico. The narrative rules of this BCG model were used to assess underwater videos of the coral reef structures and the relative coral conditions in the areas of the proposed pipeline routing. The plain

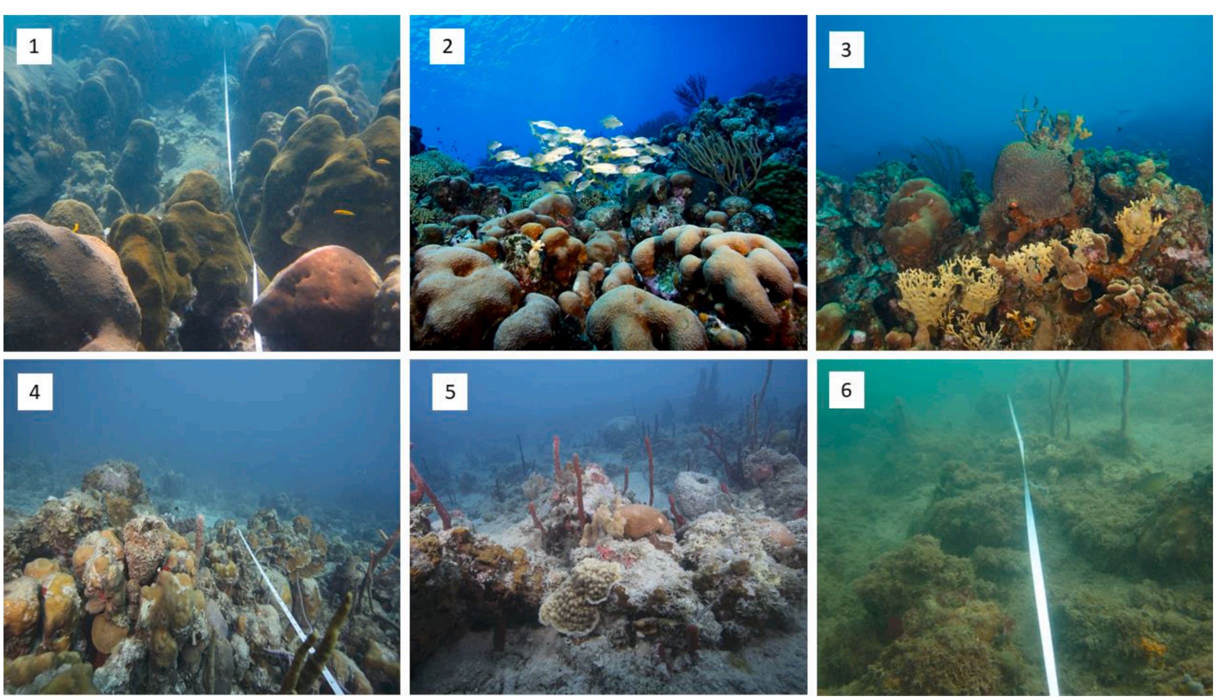

Fig. 2. Examples of reef sites for BCG levels 1–6 (as numbered in figure) that illustrate the characteristics for each narrative BCG level described in Table 5.

language in the coral reef BCG narrative framework enabled the decision makers to articulate to the company building the pipeline, the values, potential impacts, and loss of ecosystem services from those coral reef community locations near Jobos Bay National Estuarine Research Reserve. Alternative routes and locations were assessed, discussed with the pipeline contractors, and recommendations on an alternate route protective of ecologically vulnerable reefs and endangered coral species was proposed and accepted.

4.3. Case Study 3: Use of the BCG as a communication tool

A useful application of the narrative BCG model is in communicating technical challenges to non-technical stakeholders and decision makers. Biological indices often use quantitative measures of ecosystem condition based on empirical statistical distributions of different organism assemblages (e.g., percentiles of reference distributions) that can be uninterpretable to the public, stakeholders, and some resource decision makers. For coral reefs, the numeric BCG model presented in Santavy et al. (2022) may be applied directly to develop water quality standards. The narrative BCG model presented here could provide the communication tool that directly interprets the quantitative metrics into plain language. While the numeric model may facilitate development of a numeric WQS, the narrative BCG can effectively communicate the rationale for numeric WQS by describing ecological conditions associated with the different BCG levels for the nontechnical users and decision makers in terms that people understand and with criteria of societal relevance. The application of a narrative BCG has been used to support better understanding of the biological thresholds for water quality impairment in Minnesota (Gerritsen et al. 2017), Pennsylvania (US EPA, 2016), and California (Paul et al. 2020). The plain language found in the BCG narratives can effectively communicate the ecological changes associated with the BCG.

5. Discussion

Defensible criteria for coral reefs are needed to guide decision making. This requires an ability to discern the effects of human activity and an understanding of which factors contribute to a high-quality reef. Such criteria can be used to aid the restoration and maintenance of biological integrity, a long-term objective of the US CWA. Like the physical and chemical counterparts, biocriteria can be defined to protect valued biological communities (Davies and Jackson 2006; US EPA, 2016) and have been proposed for coral reef protection in the USA (Fore et al. 2009; Bradley et al. 2009, Bradley et al., 2010, Bradley et al., 2014). Here, we developed and verified a narrative (qualitative) BCG model for coral reefs with direct applications for resource managers to use in evaluating condition of a coral reef, establishing biocriteria, and considering management decisions that could impact coral reefs. It is a robust tool that can apply information from operational monitoring and assessment programs to communicate coral reef condition to the public, stakeholders, and managers and facilitate decisions or actions to protect, manage, and remediate coral reef resources.

Water quality goals to protect and restore aquatic life are cornerstones of environmental protection programs in many nations. Establishing quantitative goals is challenging because of complexities in translating species composition and abundance (biological condition) into metrics that represent terms such as “biological integrity” or “balanced ecosystem” (Paul et al. 2020). This can be disconcerting when there are limited resources for monitoring, training, issuing permits, and educating stakeholders on impacts and alternatives. BCG narrative rules use language similar to many US state aquatic life use narratives and can directly support their interpretation. The narrative rules can provide more easily understood explanations than numeric biological indices for the selection of biological integrity goals and communicating to ecological changes associated with these goals to the stakeholders (Davies and Jackson 2006; Gerritsen et al. 2017). Additionally, when biophysical metrics comprising BCG levels are linked with stressor data and measures of economic and social values and benefits, the narrative BCG can aid stakeholders and the public to better understand both environmental impacts and ecosystem services that may be at risk under different management scenarios. Ultimately, this can lead to better support for decisions to protect coral reefs (Santavy et al. 2021).

Environmental assessments using expert judgment have shown that experts can be highly concordant with numeric models in their ratings of marine benthic macroinvertebrates (Teixeira et al. 2010), marine sediment quality (Bay and Weisberg 2010), and fecal contamination studies (Cao et al. 2013). The narrative rules presented here are supported and validated by numeric BCG rules developed quantitatively using expanded datasets and presented in Santavy et al. (2022), and we refer readers to that paper for detailed analysis on how coral metric values align quantitively with BCG levels. In many BCG studies of freshwater streams, there is strong consensus on the descriptions of each BCG level and strong concordance among practitioners on the BCG level assigned to individual sites (US EPA, 2016). While the narrative rules presented here reflect the opinions and perspective of the participating panelists, the iterative nature of the BCG methodology dampens individual bias (US EPA, 2016), resulting in an authoritative consensus of experts within the focal area. Calibrated language that is developed from expert judgement can be used broadly for communicating assessment findings and uncertainty and is advocated by the Intergovernmental Panel on Climate Change (Mastrandrea et al. 2010). Rules developed by expert knowledge and judgment can reduce ambiguity (e.g., what is expected at a site, what could be gained or lost from different management scenarios) and prevent eclipsing (e.g., loss of an ecologically critical indicator through averaging of multiple metrics) compared to statistical models derived solely from empirical data. Furthermore, use of a thoroughly documented expert judgement system allows for the BCG rules and their combining functions to be fully transparent (Gerritsen et al. 2017). While we acknowledge that the inclusion of all Caribbean coral experts was not feasible, the expert panel represented over 600 years of combined experience in Caribbean coral reef biology, ecology, and taxonomy.

The process for BCG development is iterative and the model narrative can be updated and revised as new data, insights, and knowledge are gained. A critical step is the documentation of the expert logic, from both individual panel members and final panel consensus so the ecological basis and defensibility of the model is retained without having to reconvene an expert panel for future model revisions. In contrast to coral ecosystems, most freshwater ecosystems have many decades of survey data to inform the full spectrum of BCG levels, providing less uncertainty in the distinctions between BCG levels. In this model, the expert panel determined that coral reefs representative of BCG levels 1 and 2 are rare or gone entirely from most places, as indicated by global declines of coral reefs (Bradley et al. 2020; Jackson et al. 2014). However, the rarity of BCG level 1 and 2 coral reefs emphasizes the urgency of maximizing the utility of all data, historical and recent, to adopt a framework with the potential to inform where reefs are improving or declining. The current BCG model is iterative by nature, and therefore adaptable, if additional data on natural or very high-quality coral reefs become available.

A critical function of the BCG is to protect reefs by documenting conditions and attributes associated with natural reefs with the best available knowledge and information and evaluating deviations from that nature state. Coral reef condition assessments are historically limited and were not possible prior to SCUBA in the 1950s and early 1960s, at which point some coral populations had already experienced impacts (Goreau 1959; Jackson 1997; Jackson et al. 2011, Jackson et al., 2014; Pandolfi et al. 2003). These early assessments provide the best available information on the characteristics of natural Caribbean reefs undisturbed or minimally disturbed by human activity. A fully functional and intact BCG level 1 reef should not just be considered as a structure founded by hard coral, but also include components that demonstrate it is a functioning ecosystem with all processes intact. The time scale over which local or regional environmental conditions are favorable for reef development following a disturbance are most likely too short to allow for the recovery of most foundational coral reef taxa because of the intrinsic life-history characteristics of these long-lived, slow growing organisms (Jackson et al. 2011, Jackson et al., 2014). In the last five decades, significant disturbances such as thermal stress, diseases, storms, and pollution have occurred more frequently and with higher intensity, disrupting and eliminating much recovery in the ecological successional process, creating a shifting baseline for "natural" conditions (Alvarez-Filip et al. 2009; Jackson et al. 2011). Community changes in coral species can be subtle because coral species identification is challenging and substantial community changes may occur over decadal, centennial, or millennial timescales (Pandolfi et al. 2005; van Woesik et al. 2012). The potentially slow shift in coral composition emphasizes the importance of establishing and documenting natural reef conditions to help guide and define coral reef conservation and restoration goals, as documented for BCG level 1.

While the narrative BCG model represents expert consensus developed over a three-year iterative process, there were some areas where perspectives diverged. For example, most experts related reduced rugosity values to declines in reef condition scoring sites with less structure at a higher BCG level (such as levels 4, 5, and 6) indicating greater degradation. The most experienced coral reef scientists cautioned that too much emphasis was placed on low rugosity as an indicator of degraded sites. Reef rugosity is a measure of 3-dimensional surface topography that represents size and abundance for the colonies of large reef building coral species present now and in the past. Rugosity is constructed over millennial time scales by hard coral skeletons building the architectural structure accreted over centennial time scales. Decreases in rugosity, or erosion of reef topography occurs over decades, but a metric representing this rate of erosion is rarely reported as it is much more difficult to measure. A degraded reef could have very low live coral cover resulting from a past mass mortality that occurred years or even several decades ago but still have a very high rugosity value. The belief that lower rugosity always relates to degraded coral communities was not supported with the data used to develop the narrative BCG model presented here or the numeric (quantitative) BCG model presented in Santavy et al. (2022). Alternatively, sites with low rugosity values and high live coral cover could indicate favorable conditions for coral growth and high coral cover, but it might still lack solid reef accretion and development with such sites often populated by small colonies. Yet another explanation for the degraded condition could be what most experts originally assumed resulted when both rugosity and live coral cover were low, supported by a substrate quality indicating many dead coral colonies and enough time has passed for significant reef erosion. While some experts that were not involved in panel discussions may initially disagree with some conclusions made by the panel, the diverse experience and perspectives of the expert panel and the iterative, deliberative nature of the BCG development process is designed to minimize the influence of any single perspective to form an authoritative consensus (US EPA, 2016).

A significant challenge of evaluating poor or low-quality coral reefs is an understanding the distinction between anthropogenic-induced stressors and geologic features that are not conducive to sustain thriving reefs. For a BCG model to accurately describe the stressor response relationships, it is necessary to understand what biotic communities should be present at a site in the absence of anthropogenic stressors. The nature of non-live coral substrate allows these different alternatives to be evaluated in context of the geological literature describing reef formation and reef growth processes (Adey et al. 1977; Hubbard et al. 2009). However, if no evidence of the architectural reef structure is present, then it is highly unlikely there was ever robust coral reef development at the site. The inherent patchy nature of coral reef distributions makes it difficult to associate direct causality to anthropogenic stressors, particularly as stressor distribution can be either correlated with distance to land (e.g., sedimentation) or ubiquitously irregular (e.g., elevated temperatures and acidification associated with climate change). True validation of a coral reef's history and what species should be present at any location can only be determined using geological coring that can inform what coral communities were present in the past and might be possible today (Hubbard 1997; Hubbard et al. 2009). Practically, geological coring cannot be a common practice in most reef assessments because it is resource and time consuming. There was general agreement that a single transect in a bioassessment census survey is not adequate to accurately characterize the potential for sustainable biological communities in absence of human disturbance or to explain where and why reefs do or do not occur at a specified location. The panel recommended development of a more robust and statistically sound bioassessment protocol that also includes monitoring of multiple transects within a single location instead of just one as was done in the available datasets.

The narrative benthic model presented here is broadly applicable to Caribbean reefs with the potential to be expanded to other oceanic regions. While the data used for the narrative model presented here used only sites from Puerto Rico, additional data were used by this research effort to develop a numeric BCG data using additional sites from Puerto Rico and the US Virgin Islands (USVI) and is presented in Santavy et al (2022). The concurrence of the narrative model with numeric BCG traits calibrated from additional sites and locations demonstrates that the present model is directly applicable to reefs off the coast of the USVI. Similarly, the coral fish BCG model developed from this research effort has demonstrated transferability to the Florida Keys and Dry Tortugas (Bradley et al. 2020). Within other Caribbean jurisdictions, the narrative rules presented here can be used as a starting point for regional experts to refine, as needed, by using local datasets or knowledge to test rules and determine suitability. Modifications can be anticipated to adjust for species presence, abundance and distribution, and different reef zones specifically applicable to other regions or locations. Transferability of the BCG coral reef model beyond the Caribbean should be evaluated by experts of the area and tailored to coral reefs within their jurisdiction using local monitoring data and scientific expertise. This approach can provide a template for application in other well-defined coral reef habitats (e.g., deep fore reef/escarpment with coral).

The narrative BCG model for Caribbean coral reefs is one of three BCG models developed to assist with the protection and management of these ecosystems. This narrative benthic BCG model provides plain and interpretable language easily understood by nontechnical audiences. In addition to being a robust tool for condition assessment, the narrative descriptions of BCG levels provided here can be used as a robust communication tool to allow the public to appreciate and understand the trade-offs of management actions and ecosystem services. Santavy et al. (2022) validates and expands this model to include numeric (quantitative) metrics and external data sources. Additionally, the complementary BCG model for reef fishes can provide additional understanding and decision support to identify important components for biological structure (biodiversity) and function (nutrient recycling, recruitment, productivity, herbivory, growth) throughout that community (Bradley et al. 2020). The suite of BCG models presented here and in Santavy et al. (2022) and Bradley et al. (2020) provides a comprehensive toolbox for the assessment of coral reef condition and the biotic response to varying levels of stress.

CRediT authorship contribution statement

Deborah L Santavy: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Resources, Data curation, Writing – original draft, Writing – review & editing, Visualization, Project administration, Funding acquisition. **Susan K. Jackson:** Conceptualization, Methodology, Formal analysis, Investigation, Data curation, Writing – original draft, Writing – review & editing, Visualization, Project administration, Funding acquisition. **Benjamin Jessup:**

Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Resources, Visualization, Project administration. **Jeroen Gerritsen:** Conceptualization, Methodology, Software, Validation, Investigation, Data curation, Project administration. **Caroline Rogers:** Conceptualization, Methodology, Investigation, Writing – original draft, Writing – review & editing. **William S. Fisher:** Conceptualization, Methodology, Investigation, Writing – review & editing, Supervision, Funding acquisition. **Ernesto Weil:** Methodology, Investigation, Writing – review & editing. **Alina Szmant:** Methodology, Investigation, Writing – review & editing. **David Cuevas-Miranda:** Methodology, Investigation, Writing – review & editing. **Brian K. Walker:** Methodology, Investigation, Writing – review & editing. **Christopher Jeffrey:** Methodology, Investigation, Writing – review & editing. **Patricia Bradley:** Conceptualization, Methodology, Writing – review & editing. **David Ballantine:** Methodology, Investigation, Writing – review & editing. **Loretta Roberson:** Methodology, Investigation, Writing – review & editing. **Hector Ruiz-Torres:** Methodology, Investigation. **Brandi Todd:** Methodology, Investigation. **Tyler Smith:** Methodology, Investigation. **Randy Clark:** Methodology, Investigation, Data curation, Writing – review & editing. **Ernesto Diaz:** Methodology, Investigation, Writing – review & editing. **Jorge Bauzá-Ortega:** Methodology, Investigation. **Christina Horstmann:** Software, Validation, Formal analysis, Resources, Data curation, Writing – original draft, Writing – review & editing, Visualization. **Sandy Raimondo:** Writing – original draft, Writing – review & editing, Supervision.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecolind.2022.108805.

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