The Biological Condition Gradient (BCG)

A Model for Interpreting Anthropogenic Stress on the Aquatic Environment

What is the BCG?

The Biological Condition Gradient model (BCG) is a conceptual, scientific framework for interpreting biological response to anthropogenic stress. The framework is based on common patterns of biological response to stressors that have been observed by aquatic scientists across the United States (USEPA 2016) (Figure 1). It supports consistent interpretation of biological condition independent of the specific method used to collect data, the type of waterbody being assessed, or the location of the waterbody. The framework is often used in biological assessments by formalizing expert knowledge of biological conditions in quantitative models for specific aquatic systems. The models consist of quantitative decision rules that are used to assign sites to a level of condition along a stress gradient.

An Example of the BCG Using Benthic Macroinvertebrates

Levels of Biological Condition

Natural structural, functional, and taxonomic integrity is preserved.

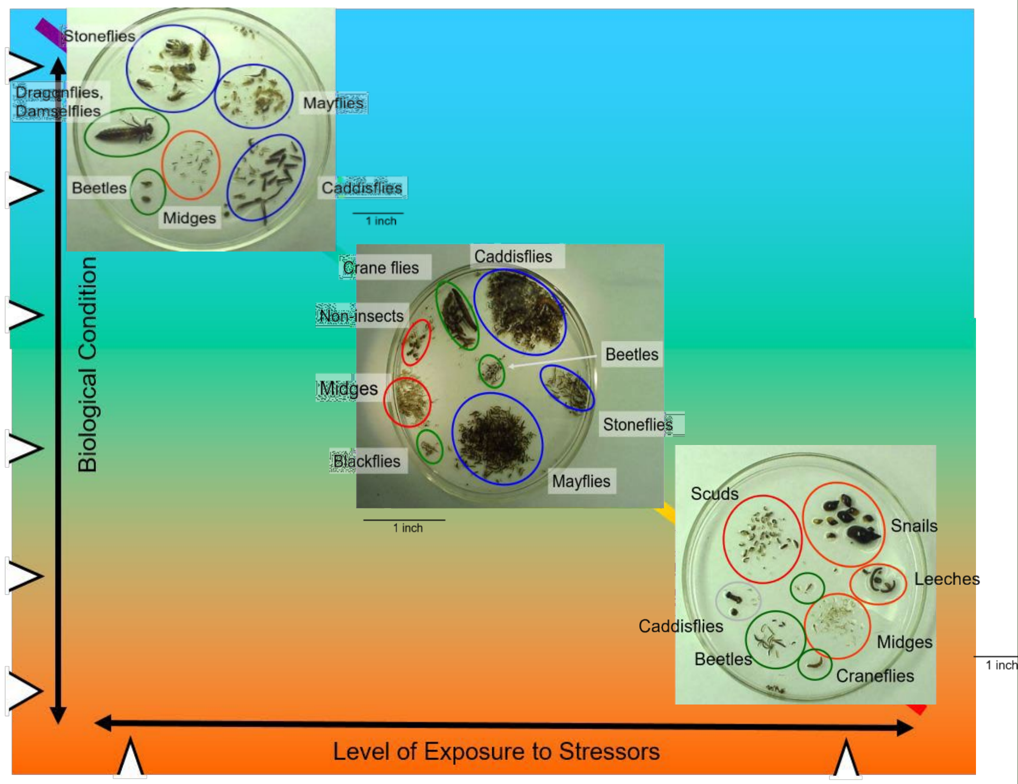
Structure & function similar to natural community with some additional taxa & biomass; ecosystem level functions are fully maintained.

Evident changes in structure due to loss of some rare native taxa; shifts in relative abundance; ecosystem level functions fully maintained.

Moderate changes in structure due to replacement of some sensitive ubiquitous taxa by more tolerant taxa; ecosystem functions largely maintained.

Sensitive taxa markedly diminished; conspicuously unbalanced distribution of major taxonomic groups; ecosystem function shows reduced complexity & redundancy.

Extreme changes in structure and ecosystem function; wholesale changes in taxonomic composition; extreme alterations from normal densities.



Watershed, habitat, flow regime and water chemistry as naturally occurs.

Chemistry, habitat, and/or flow regime severely altered from natural conditions.

Figure 1. Predicable, measurable changes in the benthic macroinvertebrate communities are observed in aquatic ecosystems in response to stress (stress increases from left to right of the diagram). For example, in these benthic macroinvertebrate samples from streams in Maine, taxa that are sensitive to stress (blue circle) typically disappear as stress levels increase while more pollution tolerant taxa (green circle, moderately tolerant) persist and highly tolerant taxa dominate at high stress levels (red circle). In some cases, such as in the assemblage shown midway on the gradient, there may be an increase in the number of taxa or individuals with initial rise in stressor levels such as nutrient pollution. *Photographs courtesy of Maine Department of Environmental Protection.*

How can the BCG be used?

In conjunction with other environmental data and information, state water quality management programs can use the BCG to:

- Consistently determine and communicate current environmental conditions relative to natural, undisturbed conditions.
- Describe, in a refined manner, what environmental conditions are attainable either through protection or restoration.
- Provide feedback on how to achieve goals for protection or restoration by tracking incremental changes in condition and assessing trends due to management actions.
- Communicate what is biologically predicted to be gained, or lost, with different management decisions.

The BCG is a flexible framework that can be applied to any waterbody and ecological region and implemented by monitoring programs that have different level of technical capabilities (e.g. one assemblage or more; annual to quarterly sampling; etc.). The more robust the monitoring program, the more confidence in the assessment.

...and, how has the BCG been used so far?

State water quality management programs have already used BCGs to:

- Designate refined aquatic life uses along a gradient of stress, e.g. excellent, good, fair;
- Develop biological criteria to measure attainment of the designated aquatic life use;
- Inform Use Attainability Analysis;
- Better understand the quality of reference sites and thus, more accurately define baseline conditions;
- Consistently describe current conditions and measure the cumulative impact of multiple stressors on aquatic life;
- Support adaptive management by tracking incremental changes in biological condition as remedial actions, controls and best management practices are implemented;
- Identify high quality waters for protection and provide an early warning signal of incremental degradation;
- Communicate to stakeholders the predicted impact of decisions on protection and management of aquatic resources.

BCG Success Stories - State Implementations of BCG Models

Minnesota, Alabama and California have incorporated the BCG as part of their biological assessment and criteria programs to complement existing biological indices or other bioassessment tools and approaches. These states have developed BCGs for their streams and assigned levels to help communicate reference-based thresholds defined by either a biological index or a predictive taxa loss model. For example, reference streams in Minnesota and Alabama typically scored at a BCG level considered "good", affirming the quality of the reference sites and providing more detailed biological description of the biota that is being protected. There was one region in Minnesota where reference streams scored lower than other regions due to both past and present regionwide impacts from agriculture and human development – corresponding with a BCG level generally considered "fair". The Minnesota BCG was used to more precisely define and communicate current conditions and establish attainable goals for aquatic life in the different regions. Like Minnesota and Alabama, California developed and compared the BCG levels of sites to independently derived bioassessment models. The scoring aligned well, and California is able to communicate to the public the meaning of reference-based biological expectations. These expectations will ultimately be used to inform levels of nutrients protective of biological condition.

What are the components of a BCG?

The Biological Condition Gradient (BCG) has two key components:

- **Attributes** are measurable components of a biological system (Karr and Chu 1999)
  Example: species composition, such as the number and proportion of sensitive and tolerant taxa
- **Levels** are the discrete levels of biological condition across a stressor-response curve. Example: Level 1 =natural; Level 6 = severely altered from natural

Attributes

The BCG framework depicts ecological condition in terms of measurable ecological characteristics, or attributes, of an aquatic community in response to anthropogenic stress. The BCG attributes correspond to the characteristics used by bioassessment programs to measure biological condition, determine restoration potential and track recovery. It is not necessary to have information from all the attributes to develop a BCG. An expert panel recommends attributes that correspond with what they consider to be the most ecologically important characteristics of the system and utilizing what data is available for model development. To date, BCG models for streams, rivers and coral reefs have primarily utilized attributes I – VI which characterize change in taxa in response to stress.

Biological and other ecological attributes used to characterize the BCG.

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 (e.g., sturgeon, American eel, pupfish, unionid mussel species).
II. Highly sensitive 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 can be found at reduced density and richness in moderately disturbed sites (e.g., many mayflies, many darter fish species).
IV. Taxa of intermediate tolerance	Ubiquitous and common taxa that can be found under almost any condition, from unstressed to highly stressed sites. They are broadly tolerant but can decline under extreme conditions (e.g., filter-feeding caddisflies, many midges, many minnow species).
V. Highly tolerant taxa	Taxa that are of low abundance in undisturbed conditions but increase in abundance in disturbed sites. Opportunistic species able to exploit resources in disturbed sites (e.g., tubificid worms, black bullhead).
VI. Nonnative or intentionally introduced	Any species not native to the ecosystem (e.g., Asiatic clam, zebra mussel, carp, European brown trout). Additionally, there are 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, disease).
VIII. Ecosystem function	Processes performed by ecosystems, including primary and secondary production; respiration; nutrient cycling; decomposition. For example, shift of lakes and estuaries to phytoplankton production and microbial decomposition under disturbance and eutrophication.
IX. Spatial/ 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 in fish composition from fluvial dependent to sunfish.
X. Ecosystem connectance	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.

Levels

The BCG has been divided into six levels of biological condition in response to increasing levels of stress (Figure 2). The six levels provide a flexible framework for a state to determine the number of levels that can be implemented. The number of levels realized will be influenced by both natural and programmatic reasons. For example, in a predominately forested perennial stream ecosystem supporting highly sensitive taxa, it may be technically possible to discriminate 6 different levels of condition based on shifts from highly sensitive to moderately sensitive to tolerant species. However, for stream systems that naturally experience high variability in flow, ranging from no flow to scouring floods in a single stream channel, species adapted to harsh conditions are expected in the natural, unstressed condition. In this scenario, it may be difficult to recognize six levels of change in species composition when the highest level of the BCG is defined by tolerant species. Additionally, some states may only be capable of discriminating three or four levels along a gradient of stress depending upon the technical capabilities of their monitoring program, while others might be capable of discerning six or more levels based on highly proficient programs and robust data sets (U.S. EPA 2013).

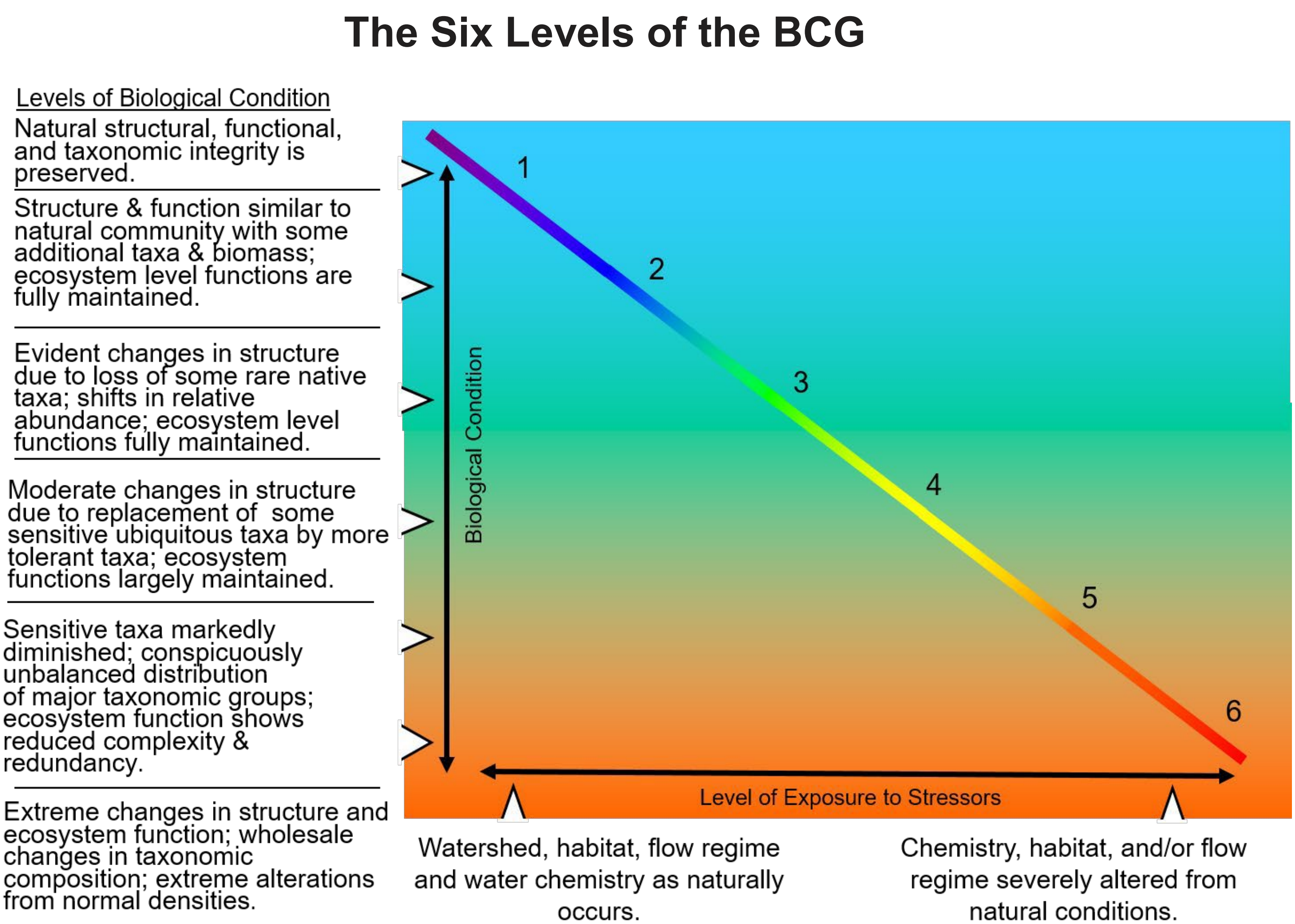
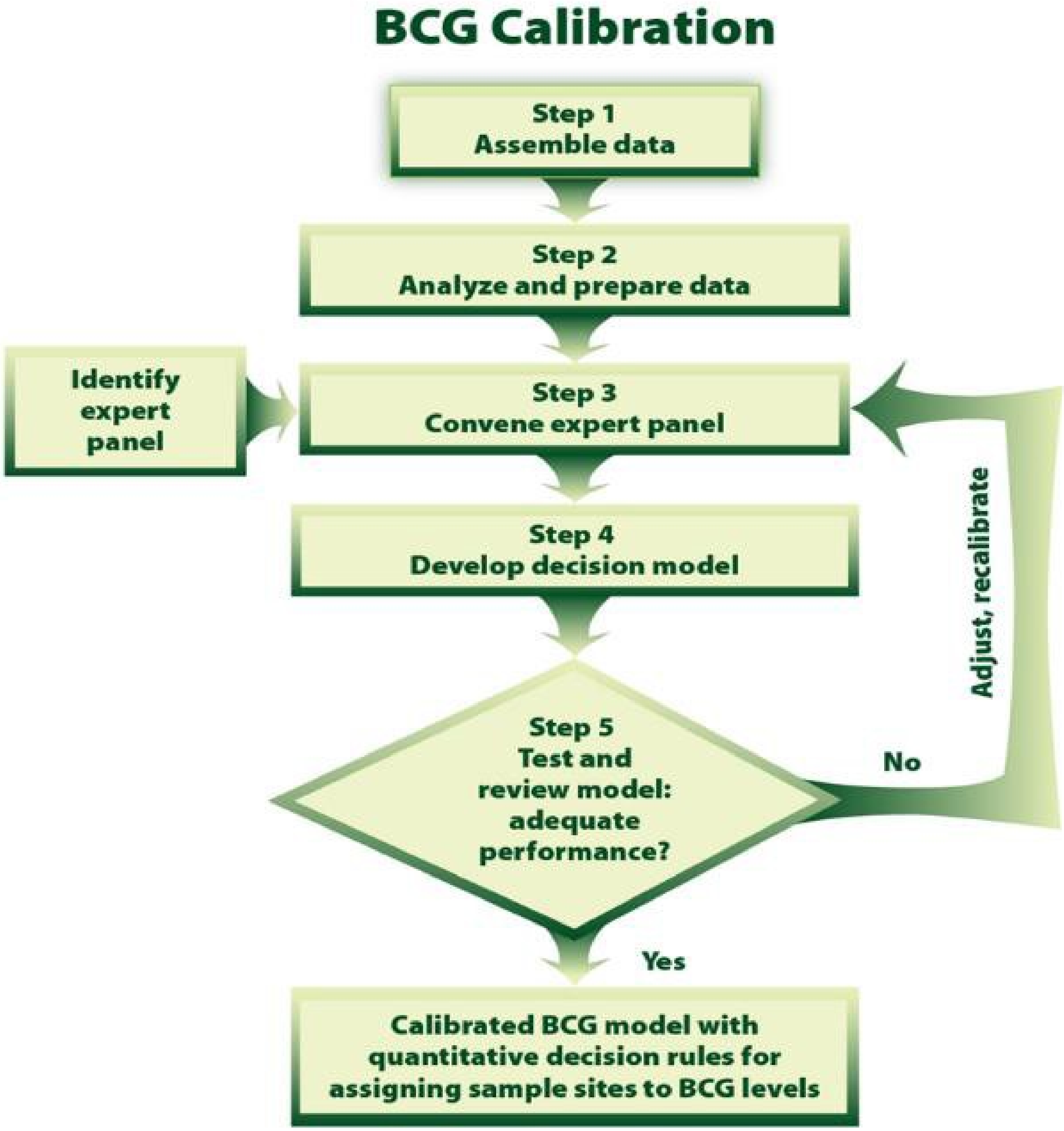


Figure 2. The Biological Condition Gradient – a scientific framework to interpret biological response to increasing effects of anthropogenic stress on aquatic ecosystems. Six levels of condition (Y axis) along a gradient of increasing stress (X axis) ranging from naturally occurring to severely altered conditions are narratively described using biological information. In this figure, the color gradient is a quick visual cue for condition level.

How is a Quantitative BCG model developed?

A key step in development of a quantitative BCG model (Figure 3) is to convene a panel with expertise in taxonomy and aquatic ecology. The panel is charged with calibrating the conceptual BCG with data for a specific aquatic system and developing quantitative decision rules for assigning sites to BCG levels for that system using a combination of expert elicitation and consensus.



Decision rules are logic statements that experts use to assign sites to BCG levels, starting with narrative statements such as "If Plecoptera richness is high in this stream, based on stream size, substrate and flow, then biological condition is close to natural, unimpacted conditions. I would assign this stream to a BCG level 2." An expert typically articulates 2 or more logic statements in making a BCG level assignment. Through an iterative process of expert elicitation and metric testing, a consensus set of quantitative decision rules for each BCG level are developed by the expert panel. The set of decision rules constitutes a BCG quantitative model for an aquatic ecosystem.

What expertise is needed on the panel?

The BCG consensus approach asks the experts to make judgments on the ecological significance of changes in the aquatic biota and come to consensus on a set of quantitative decision rules for assigning sites to BCG levels. For this approach to be credible and valid, the panel should:

- be comprised of experts with a wide and deep breadth of knowledge and expertise across the biodiversity of the region ***and not be constrained to a single agency to minimize internal bias.*** At a minimum, expertise in taxonomy and aquatic ecology specific for the waterbody and the region is required.
- have enough cumulative experience to understand what historic communities looked like and what happened to communities prior to initiation of the CWA ***to avoid defining BCG levels 1 and 2 based on existing degraded conditions.***
- include expertise in different and widely accepted methodological and analytical approaches for ***development of a robust and broadly applicable mode***

What makes an effective panel?

For the panel to successfully construct a quantitative BCG model:

- the panel's first task is to develop a detailed narrative description of physical characteristics that define pristine, or unstressed, condition for the study area. This establishes an agreed upon natural standard for evaluating site data.
- the data sets used in model development should represent the complete range of conditions that exist within the region for which the BCG is being developed.
- it is essential that the expert logic in developing the decision rules be fully documented so the reasoning underlying the rules is transparent and can be easily implemented in the future.
- panel discussion is facilitated to fully and fairly engage all experts and not allow any individual to dominate the discussion or dismiss the opinion and logic of others.
- the range of variability among experts around a site score is examined and included in model documentation so that that the strengths and limitations of the quantitative model can be clearly understood, and the model appropriately applied.

BCG Model Development

Site Data

BCG Attribute	Species Common Name	Count
IV	brook silverside	5
V	gizzard shad	1
IV	river carpsucker	4
IV	quillback	2
III	highfin carpsucker	3
III	northern hog sucker	11
IV	silver redhorse	4
III	black redhorse	10
IV	golden redhorse	45
III	shorthead redhorse	35
IV	spotfin shiner	76
VI	common carp	3
IV	redfin shiner	1
IV	hornyhead chub	1
IV	sand shiner	19

(excerpt- complete data not shown)

Expert Judgment

• Taxa Life Histories

• Field Experience

• Ecological Knowledge

Assign BCG Level Relative to Natural

What Biological Change Would Lead to a Higher or Lower BCG Level?

BCG Level Assignments

Panelist	BCG Level	Rationale
A	3	The presence /diversity of sucker and Centrarchids species (intermediate sensitive) are consistent with my experience in this size stream and my expectation for BCG level 3
B	3-	There should be more intermediate sensitive species for this size stream relative to what I expect for BCG Level 3 streams.
C	3-	Expected more diversity in general; and expected more minnow diversity (8-10 in BCG Level 3 streams of this size vs. the 5 collected), caveat: some might have been missed due to method (boat sampling vs. wadeable sampling).
D	3-	Expected more benthic species particularly with the presence of coarse substrates and low percent fines.
E	3-	There is a lack of benthic species given the presence of a firm (coarse) substrate compared to our definition of BCG Level 3 streams.
F	4	Good sucker species diversity comparable to other BCG Level 3 streams of this size, but expecting more minnow and darter species.

Median BCG Score = 3-

Figure 4. How does the panel develop numeric decision rules? Over the course of data evaluation, the expert panel develops a set of narrative and quantitative decision rules that define each BCG level. As a first step, the panel defines undisturbed and/or minimally disturbed conditions (geophysical, chemical, landform, etc) for the waterbody of interest and the region in which it is located. This serves as the shared benchmark from which the panel evaluates biological data and assigns sites to BCG levels. Data from sites representing a range of conditions, from no or low to high levels of stress, are then provided to the panel. The experts are asked to assign each site into one of the BCG levels based on its biological data including taxa lists, tolerance values, cumulative abundance data and graphs. Facilitators elicit the reasoning and metrics used by each expert in their ratings which are used to derive the rules for classifying BCG levels. This figure shows an excerpt from the recording of individual expert logic applied in assessing a stream site in Illinois using fish assemblage data, only a portion of the datasheet is shown for illustration. A plus or minus indicates a site's data does not fit 100% with an expert's expectation for a level because there are indications in the data that a site may be closer to an adjacent level in quality – either the level above (+) or below (-). This information assists the panel in articulating what they judge as a significant change that would result in a level change.

Through an iterative process combining individual expert elicitation and development of consensus, a set of narrative rules are proposed for each BCG level. Quantitative measures, or metrics, are tested for how well they replicate expert judgement and discriminate between levels (Figure 5). Following their initial development, a preliminary set of quantitative decision rules are tested by the panel with new data sets to ensure that sites are consistently evaluated and replicate their expert judgement.

BCG Level 3: 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.

Coral Reef Benthic Narrative Rule	Coral Reef Benthic Quantitative Rule
Coral cover is moderately high	**LPI coral cover ≥ 20 (10-30) %**
Coral are moderately diverse	LPI coral species > 4 (3-5) species
Sensitive Coral Species are represented	LPI Attribute II, III, + IV species > (1-3) species
Cover is mostly live and healthy organisms	**Bare substrate and algal turf with sediment < 30 (40-20) %**
Live cover of *Orbicella* is relatively high	Live cover of *Orbicella* > 20 (15-25) %

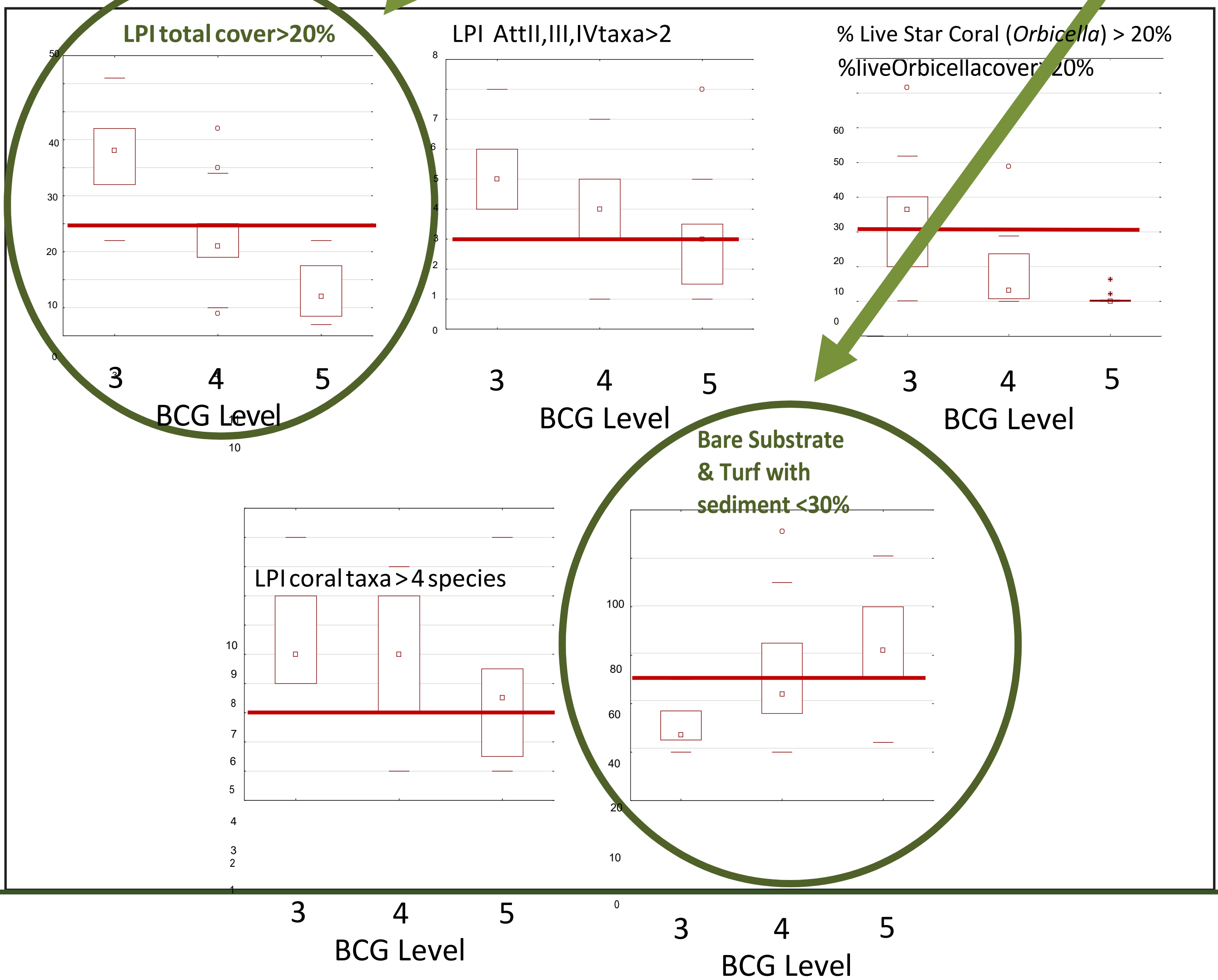


Figure 5: Metrics are tested that translate a narrative rule into a quantitative measure. If a metric does not discriminate a BCG level from another, the metric is not used. This example highlights two BCG level 3 narrative rules for coral cover (top) and the testing of the metrics for discriminating between BCG levels 3 and 4 (bottom) for coral reef communities off the coast of Puerto Rico and U.S.V.I. Box plots illustrate the median, 25th and 75th percentiles (box) and outlier values (whiskers) for a group of data. The red line represents the central decision threshold for BCG level 3 that replicates expert panel consensus. Level of confidence, or model performance, is calculated but not visually shown here.

What happens when there are no pristine or minimally stressed conditions?

Historical data and information can be used to develop a detailed narrative description or, if possible, narrative or semi-quantitative decision rules, for BCG level 1 when there are no or few pristine, or minimally stressed, conditions remaining in the region for which a BCG is to be developed. When this situation occurs, the quantitative model is developed only for those BCG levels that can be empirically defined. A detailed, narrative description of BCG level 1, and sometimes BCG level 2, can be used to more accurately communicate to the public current conditions by providing context and, in some places, serve as a narrative guide for restoration of sites assessed as close to the higher BCG level conditions.

How does the BCG model work?

A site is evaluated based on the decision rules for each level starting with the highest level of the model (Figure 6). The evaluation cascades (e.g., filters) to the next level until a BCG level is assigned.

How does the BCG model work? *Like a cascade...*

Example: coldwater sample from sit where watershed size is ≤ 10 mi² and brook trout are native*

Does the sample meet ALL BCG Level 1 criteria?

- # Total taxa < 4
- Sensitive taxa (Att I + II) - present
- Native brook trout - present
- % Sensitive taxa (Att II + III) > 50%
- % Sensitive individuals (Att II + III) > 60%
- % Tolerant (Att V + Va + VIa) individuals < 5%
- Non-native salmonids (Att VI) - absent

YES → **Assigned to BCG LEVEL 1**

NO

Does the sample meet ALL BCG Level 2 criteria?

- # Total taxa < 8
- Sensitive taxa (Att II + III) - present
- Native brook trout - present
- % Sensitive taxa (Att II + III) > 40%
- % Native brook trout: total salmonid individuals > 40%
- % Tolerant non-salmonid (Att V + Va + VIa) individuals < 10%

YES → **Assigned to BCG LEVEL 2**

NO

Does the sample meet ALL BCG Level 3 criteria?

- # Total individuals < 20
- Sensitive taxa (Att I + II) - present
- Salmonids - present
- % Sensitive taxa (Att II + II) and salmonid taxa > 25%
- % Sensitive taxa (Att II + II) and salmonid individuals > 20%
- % Non-native trout: total salmonid individuals < 70%
- % Tolerant (Att V + Va + VIa) individuals < 40%

YES → **Assigned to BCG LEVEL 3**

NO

And so on...

* In some situations, alternate rules had to be developed. For example, more taxa naturally occur in large vs. small streams, so total taxa richness rules were adjusted for watershed size. Some rules also had to be adjusted for streams in which brook trout are not native.

Figure 6. Biological data from a site are analyzed for a match with the quantitative decision rules for a BCG level.

What constitutes the final BCG model?

The final model is a set of quantitative decision rules for assigning sites to BCG levels. The rules are supported by expert knowledge and narrative descriptions for each level (Figure 7, coral reef fish assemblage rule for BCG level 3) and includes a method for entering site data (e.g. R code, database, or spreadsheet) to routinely assign sites to the appropriate BCG level.

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

Conceptual Model

Level	Attributes
GOOD - Approximate BCG Level 3	**Physical structure:** Moderate to high rugosity, moderate reef built above bedrock, some irregular cover for fish habitat, water slightly turbid, low sediment, flocs or film on substrate.
	Corals: Moderate coral diversity; large old colonies (*Orbicella*) with some tissue loss; varied population structure (usually old colonies, few middle aged & some recruitment); *Acropora* thickets maybe present; rare species absent.
	Sponges: Autotrophic species present but highly sensitive species missing.
	Gorgonians: Gorgonians more abundant than in level 1.
	Condition: Disease and tumor prevalence slightly above background level, more colonies have irregular tissue loss.
	Fish: Noticeable decline of large apex predators, groupers, snappers, etc. Small reef fish more abundant.
	Vertebrates: Large, long-lived species locally extirpated (turtles, eels).
	Other Invertebrates: *Diadema*, lobster, small crustaceans & polychaetes less abundant than level 1, large sensitive anemones species missing.
	Algae/plants: Crustose coralline algae present but less, turf algae present and longer, more fleshy algae present.

Narrative Decision Rules for Fish Assemblage

BCG Level 3	
Total Taxa	Richness moderate to high
Number of all sensitive taxa	Small to moderate proportion of richness
Total biomass (kg/km²)	Fish biomass moderate to high
Piscivores	Presence of some snappers and other piscivores
Parrotfish	Large body parrotfish present
Damselfish	Damsels do not dominate catch
Groupers	Groupers present
Reef habitat rule	More stringent
Hardbottom habitat rule	Less stringent

Quantitative Decisions Rules for Fish Assemblage

BCG Level 3	
Total Taxa	nt_total ≥ 15 (10-20) (nt = # of taxa)
Number of all sensitive taxa	nt_att23 ≥ 6 (4-8)
Total biomass (kg/km²)	bio_total ≥ 35,000 (30,000-40,000) (bio = biomass)
Piscivores	pb_SP + pb_LP > 0 (pb =% biomass)
Parrotfish	nt_Parrot2 ≥ 1 (0-2)
Damselfish	pd_damsels < 25% (20-30) (pd = % density)
Groupers	nt_Grouper > 0
Reef habitat rule*	best 6 of 7 rules
Hardbottom habitat rule*	best 5 of 7 rules

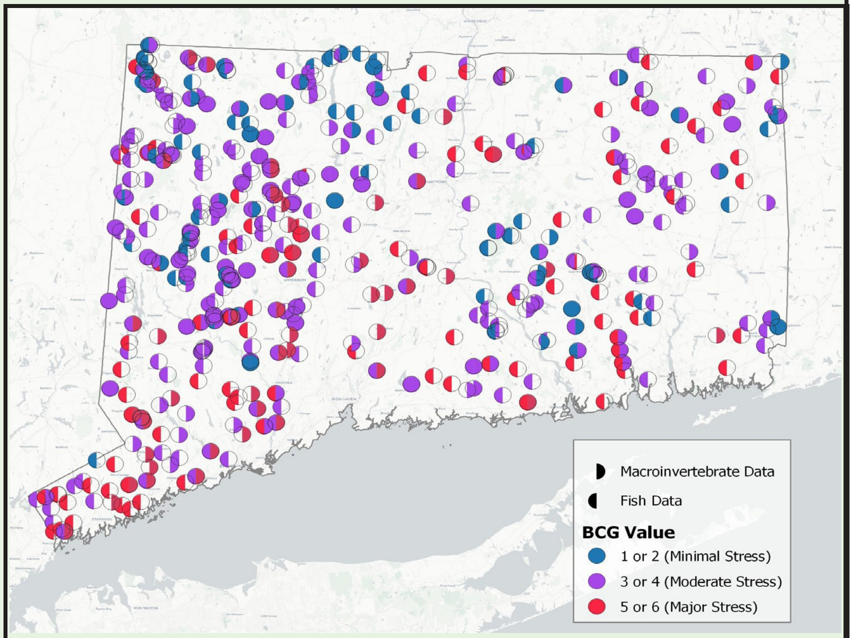
Figure 7. The BCG process is intended to explicitly link expert knowledge with statistical analysis in development of a quantitative BCG model. This example shows the sequential linkage between the conceptual level description, narrative and then numeric rules for assigning a coral reef fish community to BCG level 3. *The rules are adjusted for substrate.

BCG Success Stories - Applications of the BCG

In 2018, a BCG for benthic macroinvertebrates in Puget Sound Lowlands and Willamette Valley streams was developed by an expert panel that included scientists from King and Snohomish Counties, Oregon Department of Environmental Quality, Washington Department of Ecology, USEPA, and USGS, as well as regional taxonomists. Regional stream macroinvertebrate data (taxa lists with 500 individuals per sample) were used to develop the BCG model. The quantitative model was developed for BCG levels 2 through 6. There were no pristine conditions remaining in the study area. However, BCG level 1 was narratively defined using historic data and expert knowledge. Once the rules were defined by the experts and consensus achieved, the rules were automated in Multiple Attribute Decision Models using logic and set theory. The model replicated expert panel's decisions with over 96% accuracy. The states and counties are moving forward to use the BCG to improve communication with stakeholders, enhance their existing monitoring and assessment programs, and set restoration targets and priorities.

The state of Connecticut provides an example of how the BCG can be used to communicate with the public. As part of Connecticut's 2018 monitoring and assessment report, the state provides a web site that maps the BCG categories based on rules developed from a New England expert panel. The map illustrates the BCG levels for fish and/or macroinvertebrate assemblages and illustrates the location of sites with minimal stress, moderate stress, or major stress (From State of CT environmental web site: https://ctdeepwatermonitoring.github.io/BCGMap/).

More tools and examples will become available as states integrate the BCG into their water quality management programs.



Interested in more information?

Please contact Susan Jackson, Office of Water (Mail Code 4304T), Environmental Protection Agency, 1200 Pennsylvania Avenue NW., Washington, DC 20460or by email at jackson.susank@epa.gov

EPA Office of Water
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