

1 Running Head: The Biological Condition Gradient

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A conceptual model for interpreting detrimental change in aquatic ecosystems

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Susan P. Davies

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Maine Department of Environmental Protection

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State House Station 17

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Augusta, Maine 04333 USA

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Susan K. Jackson

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United States Environmental Protection Agency

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1200 Pennsylvania Ave

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Washington, DC 20460 USA

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1 **Abstract**

2 The United States Clean Water Act (CWA) (33 U.S. Code Sec. 1251 – 1387) provides
3 the long term, national objective to “restore and maintain the biological integrity of the Nation’s
4 waters” (sec 1251). However, the Act does not define the ecological characteristics that
5 constitute biological integrity nor does it recommend scientific methods to measure the condition
6 of aquatic biota. One way to define biological integrity was described over 25 years ago as a
7 balanced, integrated, adaptive system. Since then a variety of different methods and indices have
8 been designed and applied by states to quantify the biological condition of their waters. Because
9 states in the U.S. use different methods to determine biological condition, it is currently difficult
10 to determine if conditions vary across states or to combine state assessments to develop regional
11 or national assessments. A nationally applicable model that allows biological condition to be
12 interpreted independently of assessment methods will assist the efforts of environmental
13 practitioners in the U.S. to (1) more uniformly and directly assess aquatic resources and (2)
14 communicate more clearly to the public both the current status of aquatic resources and their
15 potential for restoration.

16 To address this need, we propose a scientific model, the Biological Condition Gradient
17 (BCG) that describes how 10 ecological attributes change in response to increasing levels of
18 human disturbance. We divide this gradient of biological condition into six tiers useful to water
19 quality scientists and managers. The model was tested by determining how consistently a
20 regionally diverse group of biologists assigned samples of macroinvertebrates or fish to the six
21 tiers. Thirty-three macroinvertebrate biologists concurred in 81% of their 54 assignments. Eleven
22 fish biologists concurred in 74% of their 58 assignments. These results support our contention
23 that the BCG represents aspects of biological condition common to all existing assessment

1 methods. We believe the model is consistent with ecological theory and will provide a means to
2 make standardized, ecologically relevant interpretations of the response of aquatic biota to
3 human disturbance. The model facilitates communication between scientists, managers, and the
4 public about how societal choices affect the protection and restoration of aquatic resources.

5

6 Key words: biological condition, biological integrity, stressors, human disturbance, Clean Water

7 Act, water quality, assessment, biological monitoring.

1 **Introduction**

2
3 Legislative context: the Clean Water Act

4 Environmental goals expressed in laws and policies articulate society’s political will to
5 preserve and restore valued aquatic resources. Two examples are the United States Clean Water
6 Act’s (CWA) (33USC1251-1387) objective to “restore and maintain the chemical, physical and
7 biological integrity of the Nation’s waters” and the European Union Water Framework Directive
8 to “restore and maintain healthy aquatic ecosystems”. Scientists provide the technical foundation
9 for implementing environmental laws and policies. They develop operational definitions and
10 methods that allow us to directly measure aquatic resource condition and, hence, attainment of
11 legislative, policy, and management goals. For example, in both the United States and the
12 European Union, scientists are collaborating with resource managers to strengthen the link
13 between current scientific advances and ecologically sound resource management (*Public*
14 *Communications*: Davies 2001 abstract 309; Johnson 2003 abstract 204; Verdonschot 2003
15 abstract 205, *Bulletin of the North American Benthological Society*,
16 <http://www.benthos.org/Publications/nabstracts.cfm>). Such collaboration enables us to better
17 organize management actions around ecological boundaries rather than political jurisdictions and
18 to communicate with the public about environmental conditions in a more meaningful and
19 consistent fashion.

20 This paper focuses on efforts in the US, guided by the CWA, to use biological
21 assessments to more uniformly and directly assess aquatic resource condition and set aquatic life
22 protection and restoration goals. The CWA integrity objective provides the long term ecological
23 goal for U.S. water quality programs but does not define the ecological components, or

1 attributes, that constitute biological integrity nor does it recommend scientific methods to
2 measure the condition of aquatic biota. One way to define biological integrity was described over
3 25 years ago (Frey 1977) and has been refined to mean a balanced, integrated, adaptive system
4 having a full range of ecosystem elements (genes, species, assemblages) and processes
5 (mutation, demographics, biotic interactions, nutrient and energy dynamics, and metapopulation
6 dynamics) expected in areas with no or minimal human influence (Karr and Dudley 1981, Karr
7 and Chu 2000).

8 However, natural aquatic systems undisturbed by human activities may not be currently
9 present or represent an achievable condition for all waters. To address this situation, the CWA
10 includes an “interim” goal for aquatic life protection and restoration that permits a socially
11 acceptable level of human disturbance while still maintaining critical elements of a natural
12 system. Under the CWA, States have the primary authority for setting water quality goals to
13 protect aquatic life for their waterbodies, i.e., designated aquatic life uses. The type of designated
14 aquatic life use (ALU) assigned to a water body can vary. For example, salmon spawning and
15 recreational fisheries are two types of ALUs. Additionally, based on societal needs and past
16 irrevocable modifications of waterbodies, states can establish ALUs that are different than
17 natural condition, e.g. waterbodies that have been significantly altered by concrete
18 channelization.

19 Over the past thirty years, States have independently developed technical approaches to
20 assess condition and set ALUs specific to their own biogeographic, regulatory, and political
21 settings. This situation has fostered innovative technical approaches, but it has complicated the
22 development of a nationally consistent approach to interpreting the condition of aquatic
23 resources. A consistent approach to interpreting biological condition will allow scientists and the

1 public to more effectively evaluate the current and potential conditions of specific waters and
2 watersheds and use that
3 information to set appropriate ALUs. Assessment results may be difficult to compare if
4 quantitative outcomes (i.e., index or indicator values) represent different qualitative conditions.
5 Additionally, without a common interpretative framework, use of different methods can hinder
6 collaboration among natural resource agencies that have complementary missions.

7 Growing frustration with the inability to effectively communicate about the ecological
8 meaning and management relevance of different quantitative measures of condition spurred our
9 attempt to articulate the conceptual underpinnings that are common to all assessment methods.
10 To address this issue, we propose a scientific model of biological degradation, the Biological
11 Condition Gradient (BCG), that encompasses the complete range of aquatic resource conditions
12 from natural to severely degraded. The model describes changes in 10 ecological attributes
13 across a gradient of deteriorating biological condition caused by increasing levels of human
14 disturbance. We divide the gradient into 6 condition tiers, tier 1 representing natural, or
15 undisturbed, conditions and tier 6 representing severely degraded conditions. The tiers describe
16 the ecological condition of the aquatic resource in terms of how close a water body is to the
17 natural state.

18 The ecological condition to support an ALU for a specific waterbody can be described in
19 terms of the BCG tiers. For example, the ecological condition needed to support salmon
20 spawning is an exceptional, high-quality natural stream and will be either a tier 1 or 2 on the
21 BCG. However, the ecological condition needed to support recreational fisheries but not salmon
22 spawning may be a tier 3 or 4. The ecological attributes that characterize the BCG tiers can be
23 measured with methods used by each state, and these condition assessments directly linked to a

1 state's ALUs. The BCG provides a rational and consistent means for determining appropriate
2 ALUs in state water quality standards and assessing whether the standards are attained.

3 At present, the model applies best to permanent, hard-bottom streams that are exposed to
4 increases in temperature, nutrients, and fine sediments. However, we expect with appropriate
5 modifications, the model will be applicable to other aquatic ecosystems and stressors. By
6 providing a common foundation for comparing biological conditions, it should be possible, even
7 when condition is measured by different methods, to more clearly communicate the ecological
8 consequences of different management choices to scientists, managers, and the public.

9

10 Existing conceptual models of biological degradation

11 Conceptual models formalize the state of knowledge and guide research. Empirically-
12 based generalizations have led to conceptual models that describe the behavior of biological
13 systems under stress (Brinkhurst 1993, Margalef 1963, 1981, Odum, et al. 1979, Rapport 1985,
14 Schindler 1987, Fausch et al. 1990, Karr and Dudley 1981). For example, Brinkhurst observed
15 that "Everyone knew (in 1929) that increases in numbers and species could be related to mild
16 pollution, that moderate pollution could produce changes in taxa so that diversity remained
17 similar but species composition shifted, and that eventually species richness declined abruptly
18 and numbers of some tolerant forms increased dramatically." Such ecosystem responses to stress
19 have been portrayed as a progression of stages that occur in a generally consistent pattern (Odum
20 et al. 1979, 1985, Rapport et al. 1985, Cairns and Pratt 1993). Establishing scientifically credible
21 and quantifiable thresholds along that progression is a priority need for resource managers
22 (Cairns 1981).

1 Conceptual models of ecosystem response to stress have been successfully used to
2 develop resource management strategies that emphasize preservation of important ecological
3 attributes. For example, Lubinski and Theiling (1999) proposed multiple narrative criteria for
4 evaluating the ecosystem health of the Upper Mississippi River. Lorentz et al. (1997) proposed
5 biotic and abiotic indicators of river condition based on theoretical concepts describing natural
6 rivers. Conceptual models of biological degradation have been legally codified for management
7 purposes in Maine and Ohio (Courtemanch et al. 1987, Yoder and Rankin 1995a). These states
8 have incorporated multiple tiers of resource quality in their water quality standards (State of
9 Maine 1985, 2003, State of Ohio 2003, Davies et al. 1995). The tiers describe both aquatic-life
10 management goals, the ALUs, and attainment criteria for different types of waterbodies.

11 For example, in Maine a waterbody is assigned to one of four management tiers by
12 considering both its existing biological condition and its highest attainable condition as
13 determined by a public and legislative process. These four tiers of biological quality in Maine's
14 Water Quality Standards are based on Odum's subsidy stress gradient (Odum et al. 1979, Odum
15 1985, Table 1). Attainment of standards is assessed by determining to which tier a sample of
16 macroinvertebrates is most similar (Courtemanch et al. 1987). Data on taxonomic composition
17 and other metrics are used in a discriminant model to identify the class of waterbody from which
18 the sample was taken. Incorporating multiple tiers has been useful for water quality management
19 in Maine in five significant ways: (1) identifying and preserving the highest quality resources,
20 (2) more accurately depicting existing conditions, (3) setting realistic and attainable management
21 goals, (4) preserving incremental improvements, and (5) triggering management action when
22 conditions decline.

1 Our goal in developing the BCG was to extend the empirical work of earlier researchers
2 and practitioners to create a nationally consistent conceptual model that could be used to better
3 link management goals for resource condition with the quantitative measures used in biological
4 assessments. The BCG was designed to describe ecological response to stress in sufficient
5 enough detail (i.e., 10 system attributes and six condition tiers) that sample data describing
6 taxonomic composition or biological indicator values could be readily placed into a tier of the
7 BCG continuum.

8 To build this model, we began with the empirical work of earlier researchers and the
9 conceptual model of Cairns et al. (1993) (Figure 1). The ideas in Cairns et al. (1993) provided
10 the conceptual foundation for the BCG because they included the concept of “natural” conditions
11 and showed how biological quality declines in relation to spatial and temporal gradients in
12 environmental quality caused by human disturbance. Early drafts of the model were modified
13 based on critiques by aquatic scientists from different biogeographic areas, each of whom had
14 fifteen to thirty years of experience in the field. Additionally, to ensure that the model would
15 have maximum potential application, we developed the tiering of the BCG based on the practical
16 experience that states have had in designing and implementing tiered aquatic life management
17 goals. We specifically designed the BCG to meet the following four objectives:

- 18 1. describes the complete scale of condition from natural to severely degraded,
- 19 2. capable of synthesizing existing field observations and generally accepted interpretations
20 of patterns of biological degradation within a common framework,
- 21 3. based on measurable, ecologically important attributes, or those likely to be measurable in
22 the future, that aid in judging the degree that a system may have departed from natural
23 condition, and

1 4. is consistent with empirical evidence documenting the trajectories of ecological attributes
2 across human disturbance gradients.

3

4 **Development of the Biological Condition Gradient (BCG) Model**

5 The BCG model was developed and tested by a national working group comprised of
6 scientists and managers from Federal, State, and Tribal water resource agencies and academia.
7 Based on recommendations from the full workgroup, a steering committee created a matrix that
8 summarized the current state of knowledge about how biological attributes change in response to
9 stress in aquatic ecosystems (Table 2, Figure 2, Digital Appendix 1). In developing the BCG, we
10 believed it was important to ground the model in both theory and ease of application. The model
11 had to have a theoretically sound context as well as meet the needs of practitioners around the
12 country. We followed an iterative, inductive approach, similar to means-end analysis (Martinez
13 1998), in building the model.

14 We entered the process of model building by testing whether biologists from different
15 parts of the country would draw similar conclusions regarding the condition of a waterbody from
16 simple lists of organisms and their counts. Our approach was based on Maine's experience in
17 which expert biologists independently assigned samples of macroinvertebrates to *a priori*
18 defined classes of biological condition defined by differences in assemblage attributes (Davies et
19 al. 1995). In Maine, decision rules were provided to biologists in the form of a 4 X 31 matrix of
20 expected trajectories of quantifiable aspects of the invertebrate assemblage that corresponded
21 with biological expectations for four water quality classes (A, B, C and Non-Attainment, Table
22 1). The high level of agreement among experts in placing samples into different classes allowed
23 Maine to develop a predictive statistical model that is now used to assess the biological condition

1 of new sites (Courtemanch 1995, Shelton and Blocksom 2004, Davies et al, unpublished
2 manuscript).

3 The BCG describes ecological condition in terms of 10 key attributes expressed at
4 different spatial scales. In biological assessments, most information is collected at the spatial
5 scale of a site or reach and the temporal scale of a single sampling event. Many of the attributes
6 that contribute to the BCG are based on these scales. Site scale attributes include aspects of
7 taxonomic composition and community structure (Attributes I-VI) and organism and system
8 performance (Attributes VII and VIII). To address larger temporal and spatial scales, physical-
9 biotic interactions are also included (Attributes IX and X) because of their importance in
10 evaluating and prioritizing intervention actions and in determining rehabilitation potential. To
11 provide a practical framework for practitioners, we describe how each of these attributes varies
12 across six tiers of biological degradation (Digital Appendix 1). We recognize that some
13 monitoring programs may be unable to distinguish, or may not require, six tiers. However, the
14 workgroup members concluded that this degree of resolution in the BCG would help compare
15 results more consistently across monitoring programs. Finally, the general model is described in
16 terms of the biota of a specific region (Maine) to illustrate how specific ecological attributes vary
17 across the BCG tiers (Digital Appendix 2). In the Maine example we describe how the relative
18 densities of specific taxa of varying sensitivities to disturbance change across tiers. This example
19 is based on 20 years of biomonitoring data.

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21 Taxonomic composition and tolerance (Attributes I-V).

22 Taxa differ in their sensitivities to stress, and changes in the number and kinds of taxa
23 present and the distribution of individuals among taxa across disturbance gradients are important
24 and useful indicators of detrimental effects (Cairns 1977, Karr 1981). Sensitivity of taxa to stress

1 can vary both among species and with stressor. Shifts in taxa as a function of differing
2 sensitivities to aquatic and riparian disturbance are well-documented (Table 3). Disturbance
3 tends to select for short-lived, tolerant species and against longer-lived, less tolerant species
4 (Pianka 1970, Odum 1985, Rapport et al., 1985). In the highest quality tiers of the gradient,
5 locally endemic taxa that are long-lived and ecologically specialized are well-represented and the
6 relative abundances of generalists and pollution-tolerant organisms are low. With increasing
7 stress, assemblage composition shifts towards tolerant species or short-lived taxa that can rapidly
8 colonize disturbed environments. Assemblages in the lower tiers are dominated by eurytopic taxa
9 with generalist or facultative feeding strategies.

10

11 Non-native taxa (Attribute VI).

12 This attribute represents both an effect of human disturbance and a stressor in the form of
13 biological pollution. Although some intentionally introduced species are valued by large
14 segments of society (e.g., gamefish), these species may be just as disruptive to native species as
15 undesirable opportunistic invaders (e.g., zebra mussels). Many rivers in the USA are now
16 dominated by non-native fishes and invertebrates (Moyle 1986), and introductions of alien
17 species are the second most important factor contributing to fish extinctions in North America
18 (Miller et al. 1989). The BCG identifies maintenance of native taxa as an essential characteristic
19 of Tier 1 and 2 conditions. The model only allows for the occurrence of non-native taxa in these
20 tiers if those taxa do not displace native taxa or have a detrimental effect on native structure and
21 function. Tiers 3 and 4 depict increasing occurrence of non-native taxa. Extensive replacement of
22 native taxa by tolerant or invasive, non-native taxa occurs in Tiers 5 and 6.

23

1 Organism Condition (Attribute VII)

2 Organism condition includes direct and indirect indicators such as fecundity, morbidity,
3 mortality, growth rates, and anomalies such as lesions, tumors, and deformities. Some of these
4 indicators are readily observed in the field and laboratory, whereas the assessment of others
5 requires specialized expertise and much greater effort. The most common approach for state and
6 tribal programs is to forego complex and demanding direct measures of organism condition (e.g.,
7 fecundity, morbidity, mortality, growth rates) in favor of indirect or surrogate measures (e.g., %
8 of organisms with anomalies, age or size class distributions). Organism anomalies in the BCG
9 vary from naturally occurring incidence in Tiers 1 and 2 to higher than expected incidence in
10 Tiers 3 and 4. In Tiers 5 and 6, biomass is reduced, the age structure of populations indicates
11 premature mortality or unsuccessful reproduction, and the incidence of serious anomalies is high.

12
13 Ecosystem function (Attribute VIII)

14 The “functional integrity” of an ecosystem is a broad and poorly defined concept that
15 refers to the aggregate performance of dynamic interactions among an ecosystem’s biological
16 parts (Cairns 1977). In this paper, we use the term “ecosystem function” to include measures of
17 both the interactions among taxa (food web dynamics) and energy and nutrient processing rates
18 (energy and nutrient dynamics). These attributes are included in the BCG because their
19 fundamental importance is universally recognized by ecologists. At this time the level of effort
20 required to directly assess properties of functional integrity is beyond the means of most state
21 and tribal monitoring programs. Instead, most programs rely on taxonomic and structural
22 indicators to make inferences about functional status (Karr et al. 1986). For example, shifts in the
23 primary source of food may cause changes in trophic guild indices or indicator species. Although

1 direct measures of ecosystem function are currently difficult or time consuming, they may
2 become practical in the future.

3 Attribute VIII includes aspects of individual, population, and community condition.

4 Altered interactions between individual organisms and their abiotic and biotic environments may
5 result in changes in growth rates, reproductive success, movement, or mortality. These altered
6 interactions are ultimately expressed at ecosystem-levels of organization (e.g., shifts from
7 heterotrophy to autotrophy, onset of eutrophic conditions) and as changes in ecosystem process
8 rates (e.g., photosynthesis, respiration, production, decomposition) (Table 4). To illustrate
9 dynamic processes such as these the Maine case example (Digital Appendix 2) describes a
10 progression of functional change. It presents a naturally oligotrophic and heterotrophic system
11 with $P/R < 1$, in Tiers 1 and 2. Tiers 3 and 4 show functional changes commonly associated with
12 the effects of increased temperature and nutrient enrichment ($P/R > 1$, diurnal sags in dissolved
13 oxygen, changes in taxonomic composition and relative abundance, increased algal biomass).
14 Tier 5 describes an autotrophic system impaired by excessive algal biomass. Poor water quality
15 described in Tier 6 results in negligible algal production. The resulting low photosynthesis and
16 high bacterial respiration causes a reversal back to heterotrophy and $P/R < 1$.

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18 Scale-dependent features (Attributes IX and X).

19 Attribute IX describes the spatial and temporal extent of detrimental effects and Attribute
20 X describes changes in ecosystem connectance across a disturbance gradient. Both attributes are
21 associated with alterations that occur within entire catchments, basins, and regions, or within
22 seasonal and annual cycles. These attributes were included in the BCG because the extent of
23 ecosystem alteration has important management implications in terms of an individual

1 waterbody's risk of further degradation as well as its rehabilitation potential. For example,
2 ecosystem connectivity is fundamental to the successful recruitment and maintenance of
3 organisms into any environment. A single impaired stream reach in an otherwise intact
4 watershed has far more restoration potential than a similar site in a basin that has undergone
5 extensive, land use alteration (Table 3). Tiers 1 and 2 depict a highly connected system in which
6 a natural disturbance regime is maintained. Detrimental effects in Tiers 3 and 4 are limited to the
7 reach or seasonal scale. The two lowest tiers depict a system with detrimental effects extending
8 to the catchment scale and affecting multiple seasons. A few "islands" of adequate
9 physical/chemical conditions may serve as refugia in Tier 5, but extensive loss of connectance
10 and refugia occurs in Tier 6.

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12 **Evaluation of the Biological Condition Gradient Model**

13 To test the general applicability of the BCG to sampling data taken from real ecosystems,
14 we evaluated how consistently individual biologists classified samples of aquatic biota based on
15 the attributes incorporated into the BCG. Governmental and research biologists from 23 states
16 and one tribe participated in the data exercise. The full workgroup was divided into five breakout
17 groups according to regional (Northeast, Southeast, Northwest, Great Plains) or assemblage
18 (fish, invertebrates) expertise. We used invertebrate and fish data sets in which samples were
19 selected to span as many of the tiers described in the BCG as possible. The 54 invertebrate
20 samples and 58 fish samples used in the tests were collected from six different regions within the
21 U.S. (Northeast, Mid-Atlantic, Southeast, Northwest, Southwest, Central) and included only
22 taxonomic names, densities, and in some cases, index values. Individuals were asked to place
23 each sample into one of the six condition tiers but were cautioned not to apply a simple relative

1 quality ranking, because all six tiers of degradation did not necessarily occur within the data sets.
2 We then calculated percent concurrence among the individuals to assess the level of agreement
3 among biologists when applying the BCG to raw data.

4 In the first stage of the data exercise, we evaluated between-biologist differences by
5 asking work group participants to rate a single data set of 6-8 samples. The breakout groups then
6 were asked to classify samples from larger and more variable datasets. We asked breakout
7 groups to summarize their interpretations and how consistent they were by region, and to identify
8 biological responses to degrading conditions that were not captured by the BCG. We further
9 asked them to identify which tiers corresponded to their understanding of (1) the CWA meaning
10 of biological integrity and (2) the CWA interim goal for protection and propagation of aquatic
11 life.

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13 **Outcome of the Evaluation: level of concurrence and recommended revisions**

14 Workgroup members placed 81% of the 54 benthic macroinvertebrate samples and 74%
15 of the 58 fish samples into the same BCG tiers. When assignments differed, they were usually
16 within one tier's distance in either direction. Following full workgroup discussion, tiers were
17 revised so that transitions were more distinct. Each of the breakout groups independently
18 reported that the ecological characteristics described by Tiers 1 through 4 were indicative of the
19 CWA's interim goal for protection and propagation of aquatic life. These groups also identified
20 the characteristics described by Tiers 1 and 2 as indicative of biological integrity. Further, the
21 breakout groups independently and unanimously agreed that the conditions described by Tiers 5
22 and 6 represented a severe level of biological degradation that did not meet the CWA's interim
23 goal.

1 Workgroup members reported that key concepts were important with respect to
2 classifying samples into tiers and identifying boundaries between tiers. For Tiers 1 and 2,
3 biologists identified the maintenance of native species populations as essential to their
4 understanding of biological integrity. Although many participants noted that criteria for
5 distinguishing differences between tiers in Attribute VIII (Ecosystem Function) were poorly
6 defined, most nevertheless identified changes in ecosystem function (as indicated by marked
7 changes in food-web structure and guilds) as critical in distinguishing between Tiers 4 and 5.

8 Discussion following administration of the BCG exercise revealed that participants
9 readily agreed on some of the condition attributes but not on others. Participants indicated they
10 mostly used Attributes I-V (taxonomic composition and tolerance), Attribute VI (non-native
11 taxa, for Tiers 2-6 only) and Attribute VII (organism condition) to evaluate biological conditions.
12 In contrast, because Attributes VIII - X (ecosystem function and scale-dependent features) are
13 rarely directly assessed by biologists, the evaluation of these attributes was accompanied by
14 relatively high uncertainty. Even so, workgroup members strongly advocated retaining these
15 attributes in the BCG because of the practical use of this information in making decisions on
16 restoration.

17 The presence of non-native taxa in Tier 1 was also the subject of considerable discussion.
18 Knowledge of the extensive occurrence of some non-native taxa in otherwise near-pristine
19 systems conflicted with the desire by many to maintain a conceptually pure and natural tier.
20 Further discussion resulted in agreement that the presence of non-native taxa in Tier 1 was
21 permissible only if they cause no displacement of native taxa, although the practical uncertainties
22 of this provision were acknowledged. We also discussed the applicability of the BCG when
23 threatened or endangered species occur. Workgroup members concluded that because Attributes

1 I and II (e.g., historically documented and sensitive taxa) assess the status of native taxa, these
2 attributes should also identify threatened or endangered species when classifying a site or
3 assessing its condition.

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Discussion

6 The BCG was designed to facilitate more accurate communication about the
7 environmental consequences of society's choices regarding the management of aquatic
8 resources. For example, the deliberate grounding of the BCG in natural conditions will help
9 practitioners and the public recognize that current conditions do not necessarily represent natural
10 conditions. In areas where natural, or near-natural conditions exist, people are generally familiar
11 with what is natural and what is degraded. But, many of the workgroup members with
12 experience in extensively altered regions observed that practitioners and the public alike tend to
13 accept the "best of what is left" as the optimal recovery potential for a system. In these places, it
14 is difficult to visualize those natural conditions that were once present, which results in a
15 truncated perspective on which to base decisions. Natural conditions may not be achievable in
16 many places, but an improved understanding of the changes that have occurred will result in a
17 more rigorous evaluation of what remains and what could be restored.

18 Critical gaps in our knowledge were uncovered during the development of the BCG. For
19 example, the workgroup identified the need for regional evaluations of species tolerance to
20 stressors associated with human disturbance. Tolerance information presented in the current
21 version of the BCG tends to be based on generalized taxa responses to a non-specific human
22 disturbance gradient. At this time, tolerance information is not available for most taxa and for
23 many common stressors (temperature, nutrients, sediments). In some cases, tolerance values are

1 based on data collected in other geographic regions or for other purposes (e.g., Von Damm's
2 European diatom tolerances are used for North American taxa). Improved tolerance value
3 information is needed to both refine application of the BCG and evaluate probable causes of
4 biological degradation when developing restoration or remediation strategies.

5 Additionally, taxa that are considered tolerant to human disturbance in one region of the
6 country may not be classified that way in another region. For example, long-lived taxa have
7 generally been characterized as sensitive to increasing human disturbance and tend to be
8 replaced by short-lived taxa in stressed systems. As such, the presence of long-lived taxa in a
9 waterbody has been used to indicate high quality conditions, whereas the predominance of short-
10 lived taxa indicate degradation. However, in the arid western U.S., extreme changes in hydrology
11 define the natural regime for some systems, and an opposite trend has been observed; short-lived
12 taxa can dominate the biological community in natural settings. In these systems, a shift to long-
13 lived taxa may be an indicator of altered, less variable flow regimes.

14 The development of the BCG brought the role of science in management into sharper
15 focus. One such issue was the presence of introduced or invasive species in otherwise high-
16 quality, aquatic systems. As mentioned earlier, the workgroup unanimously agreed that
17 maintenance of native species populations was the key determinant for membership in Tiers 1 or
18 2, the biological integrity categories. However, the role of introduced or invasive species within
19 these highest categories was vigorously debated. The resulting tier descriptions, allowing for
20 nonnative species in the highest tiers as long as there is no detrimental effect on the native
21 populations, has practical management implications. For example, introduced European brown
22 trout (*Salmo trutta*) have replaced native brook trout (*Salvelinus fontinalis*) in many eastern U.S.
23 streams. In some catchments, brook trout persist only in stream reaches above waterfalls that are

1 barriers to brown trout, even though downstream reaches are nearly pristine except for the
2 presence of brown trout (D. Lenat, North Carolina Department of Natural Resources, personal
3 communication). In these places, if stream habitat is preserved throughout the catchment, brook
4 trout can potentially repopulate downstream reaches if society decided to remove the introduced
5 brown trout. Assigning the goal for the catchment to the highest tier will help focus public
6 attention and target appropriate management actions to preserve brook trout where present and
7 maintain potential for restoration where they are not.

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Conclusions

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The BCG is a conceptual model of ecological degradation that synthesizes scientific knowledge with the practical experience and needs of resource managers. We developed the BCG model to serve as an underlying, heuristic framework that (1) synthesizes what we know into testable hypotheses and (2) identifies knowledge gaps in need of further research. By modifying the model for individual regions, scientific knowledge can be reviewed and consolidated and research needs can be expressed in a context relevant to management. Although regional modifications will be needed (Table 5), biologists from across the U.S. agreed that a similar sequence of biological degradation occurs in streams in response to anthropogenic stress. This agreement supports the feasibility of using the BCG as a common framework to guide management decisions to protect and restore aquatic systems in the U.S.

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Use of the BCG should promote implementation of consistent policies and management by applying a common accounting framework to diverse, extant conditions. At the national level, it should allow us to translate different regional and state assessment measures and standards to a common yardstick. At the regional and state level, the BCG should facilitate organizing

1 management actions along ecological rather than political boundaries. The BCG tiers should
2 provide a means for regional and state resource managers to identify outstanding resources,
3 recognize incremental improvements in degraded locations, and appropriately allocate resources
4 and management actions.

5 We believe future work should focus on developing a comparable model for tiering the
6 human disturbance gradient (HDG) and quantifying the relationships between the BCG and both
7 general and stressor-specific HDGs (Allan et al. 1997, Yuan and Norton 2003, Hughes,
8 unpublished manuscript). A HDG model will assist us in better interpreting the BCG by helping
9 us know what reference is and how biology responds to different types of individual and
10 cumulative stressors. These are especially important issues to address because (1) least-disturbed
11 'reference' sites differ significantly across states and ecoregions in their departure from historical
12 or natural conditions, and (2) the expected biotic response to otherwise similar gradients of
13 landscape alteration likely vary in different parts of the country (Hughes et al. 1986, Hughes
14 1994, Bryce et al. 1999, Wallin et al. 2003, Stoddard et al. this issue). The integration of BCG
15 and HDG models should ultimately provide us with a comprehensive approach to evaluate
16 ecological condition (biological, physical and chemical) and to more effectively target
17 management actions for either preservation or remediation.

18

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- 1 TABLE 1. Maine's narrative aquatic life and habitat standards for rivers and streams M.R.S.A
 2 Ch. 579 Title 38 Article 4-A § 464-465).

| <u>Class</u> | <u>Biological Standard</u> |
|--------------|--|
| AA* | Habitat shall be characterized as natural and free flowing. Aquatic life shall be as naturally occurs.* |
| A | Habitat shall be characterized as natural. Aquatic life shall be as naturally occurs. |
| B | Habitat shall be characterized as unimpaired. Discharges shall not cause adverse impacts to aquatic life. Receiving water shall be of sufficient quality to support all aquatic species indigenous to the receiving water without detrimental changes in the resident biological community. |
| C | Habitat for fish and other aquatic life. Discharges may cause some changes to aquatic life, provided that the receiving waters shall be of sufficient quality to support all species of fish indigenous to the receiving water and maintain the structure and function of the resident biological community. |
| Impoundments | Support all species of fish indigenous to those waters and maintain the structure and function of the resident biological community. |

*The narrative aquatic life standard is the same for Class AA and Class A.

TABLE 2. Narrative descriptions of the 10 attributes that distinguish the six tiers of the Biological Condition Gradient.

| Biological Condition Gradient Tiers | | | | | | |
|---|---|--|---|--|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 |
| | Natural or native condition | Minimal changes in structure of the biotic community and minimal changes in ecosystem function | Evident changes in structure of the biotic community and minimal changes in ecosystem function | Moderate changes in structure of the biotic community and minimal changes in ecosystem function | Major changes in structure of the biotic community and moderate changes in ecosystem function | Severe changes in structure of the biotic community and major loss of ecosystem function |
| General Description of Biological Condition | | | | | | |
| Attributes | Native structural, functional and taxonomic integrity is preserved; ecosystem function is preserved within the range of natural variability | Virtually all native taxa are maintained with some changes in biomass and/or abundance; ecosystem functions are fully maintained within the range of natural variability | Some changes in structure due to loss of some rare native taxa; shifts in relative abundance of taxa but sensitive-ubiquitous taxa are common and abundant; ecosystem functions are fully maintained through redundant attributes of the system | Moderate changes in structure due to replacement of some sensitive-ubiquitous taxa by more tolerant taxa, but reproducing populations of some sensitive taxa are maintained; overall balanced distribution of all expected major groups; ecosystem functions largely maintained through redundant attributes | Sensitive taxa are markedly diminished; conspicuously unbalanced distribution of major groups from that expected; organism condition shows signs of physiological stress; system function shows reduced complexity and redundancy; increased build-up or export of unused materials | Extreme changes in structure; wholesale changes in taxonomic composition; extreme alterations from normal densities and distributions; organism condition is often poor; ecosystem functions are severely altered |
| I Historically documented, sensitive, long-lived or regionally | As predicted for natural occurrence except for global extinctions | As predicted for natural occurrence except for global extinctions | Some may be absent due to global extinction or local extirpation | Some may be absent due to global, regional or local extirpation | Usually absent | Absent |

Davies and Jackson

endemic taxa

| | | | | | | |
|---|---|--|--|---|--|---|
| II Sensitive-rare taxa | As predicted for natural occurrence, with at most minor changes from natural densities | Virtually all are maintained with some changes in densities | Some loss, with replacement by functionally equivalent sensitive-ubiquitous taxa | May be markedly diminished | Absent | Absent |
| III Sensitive-ubiquitous taxa | As predicted for natural occurrence, with at most minor changes from natural densities | Present and may be increasingly abundant | Common and abundant; relative abundance greater than sensitive-rare taxa | Present with reproducing populations maintained; some replacement by functionally equivalent taxa of intermediate tolerance | Frequently absent or markedly diminished | Absent |
| IV Taxa of intermediate tolerance | As predicted for natural occurrence, with at most minor changes from natural densities | As naturally present with slight increases in abundance | Often evident increases in abundance | Common and often abundant; relative abundance may be greater than sensitive-ubiquitous taxa | Often exhibit excessive dominance | May occur in extremely high or extremely low densities; richness of all taxa is low |
| V Tolerant taxa | As predicted for natural occurrence, at most minor changes from natural densities | As naturally present with slight increases in abundance | May be increases in abundance of functionally diverse tolerant taxa | May be common but do not exhibit significant dominance | Often occur in high densities and may be dominant | Usually comprise the majority of the assemblage; often extreme departures from normal densities (high or low) |
| VI Non-native or intentionally introduced taxa | Non-native taxa, if present, do not displace native taxa or alter native structural or functional integrity | Non-native taxa may be present, but occurrence has a non-detrimental effect on native taxa | Sensitive or intentionally introduced non-native taxa may dominate some assemblages (e.g., fish or | Some replacement of sensitive non-native taxa with functionally diverse assemblage of non-native taxa of | Some assemblages (e.g., fish or macrophytes) are dominated by tolerant non-native taxa | Often dominant; may be the only representative of some assemblages (e.g., plants, fish, bivalves) |

Davies and Jackson

| | | | | | | |
|--|---|---|--|---|---|---|
| | | | macrophytes) | intermediate tolerance | | |
| VII Organism condition (especially of long-lived organisms) | Any anomalies are consistent with naturally occurring incidence and characteristics | Any anomalies are consistent with naturally occurring incidence and characteristics | Anomalies are infrequent | Incidence of anomalies may be slightly higher than expected | Biomass may be reduced; anomalies increasingly common | Long-lived taxa may be absent; biomass reduced; anomalies common and serious; minimal reproduction except for extremely tolerant groups |
| VIII Ecosystem functions | All are maintained within the range of natural variability | All are maintained within the range of natural variability | Virtually all are maintained through functionally redundant system attributes; minimal increase in export except at high storm flows | Virtually all are maintained through functionally redundant system attributes though there is evidence of loss of efficiency (e.g., increased export or decreased import) | Apparent loss of some ecosystem functions manifested as increased export or decreased import of some resources, and changes in energy exchange rates (e.g., P/R, decomposition) | Most functions show extensive and persistent disruption |
| IX Spatial and temporal extent of detrimental effects | N/A A natural disturbance regime is maintained | Limited to small pockets and short duration | Limited to the reach scale and/or limited to within a season | Mild detrimental effects may be detectable beyond the reach scale and may include more than one season | Detrimental effects extend far beyond the reach scale leaving only a few islands of adequate conditions; effect extends across multiple seasons | Detrimental effects may eliminate all refugia and colonization sources within the catchment and affect multiple seasons |
| X Ecosystem connectance | System is highly connected in space and time, at least annually | Ecosystem connectance is unimpaired | Slight loss of connectance but there are adequate local recolonization sources | Some loss of connectance but colonization sources and refugia exist within the catchment | Significant loss of ecosystem connectance is evident; recolonization sources do not exist for some taxa | Complete loss of ecosystem connectance in at least one dimension (i.e., longitudinal, lateral, vertical, or temporal) lowers reproductive success of most |

groups; frequent
failures in
reproduction and
recruitment

Table 3. Observational evidence in support of the predicted responses of the ecological attributes in the Biological Condition Gradient.

| BCG Attributes and Response | Case-specific Documentation | Reference |
|---|---|--|
| <u>Attributes I – V</u> | | |
| 1) Shifts in the numbers and kinds of species present, and in the number of individuals per species, as a function of varying tolerances to different kinds of aquatic and riparian disturbance | Changes in lake diatom species composition in response to intentional fertilization. Loss of sculpins downstream of metal mines. Changes in algal species across a nutrient gradient in the Florida Everglades. Changes in diatom assemblages with increased acidification and eutrophication of lakes. Shifts in species composition along a gradient of pulp and paper mill effluent concentration in a Maine river. Shifts in damselfly species from specialist species to generalist species along a gradient of organic pollution in an Italian river. Variable sensitivities of benthic macroinvertebrate species to acidic conditions. | Zeeb et al. 1974, Yang et al. 1996 Mebane et al. 2003 Stevenson et al. 2002 Dixit et al. 1999 Rabeni et al. 1988 Solimini et al. 1997 Courtney and Clements 2000 |

| | | |
|---|--|--|
| | Changes in fish species composition in an Oregon river with increased nutrients and temperature. | Hughes and Gammon 1987 |
| | Changes in fish species composition in response to human disturbance. | Hughes et al. 1998, Hughes and Oberdorff 1998 |
| | Differentially tolerant fish species in response to heavy metal and dissolved oxygen gradients in two Indian rivers. | Ganasan and Hughes 1998 |
| | Variable responses of stream amphibians to severe siltation. | Welsh and Ollivier 1998 |
| 2) Shifts from K-selected strategists to r-selected strategists following disturbance | Shifts from fragmentation-sensitive to fragmentation-tolerant bird species in relation to disturbed riparian habitats. | Croonquist and Brooks 1993, Allen and O'Connor 2000, Bryce et al. 2002a, 2000b |
| | Higher proportion of r-selected species in a flow regulated river as compared to a natural flow regime river. | Nilsson et al. 1991 |
| | Shift to r-selected, generalist damselfly species along a gradient of increasing pollution. | Solimini et al. 1997 |

| | | |
|---|---|---------------------------------|
| | Water-level fluctuation in a mesocosm resulted in increased proportion of r-strategist species. | Troelstrup and Hengenrader 1990 |
| | High pollution stress correlated with increase in r-selected strategists in the same river 21 years apart. | Richardson et al. 2000 |
| 3) Regional and national species attribute lists and taxonomic tolerance values | Compendium of pollution tolerance, habitat preferences, feeding guilds for fish species of the northeastern U.S. | Halliwell et al. 1998 |
| | Compendium of pollution tolerance, habitat preferences, feeding guilds for fish species of the Pacific Northwest, U.S. | Zaroban et al. 1999 |
| | Organic pollution tolerance ranks for Wisconsin stream insect taxa. | Hilsenhoff 1987 |
| | Compendium of pollution tolerance, habitat preferences, feeding guilds of North American fish and aquatic macroinvertebrate taxa. | Barbour et al. 1999 |

Attribute VI

| | | |
|--|--|---|
| Detrimental effects of non-native taxa | Loss of 150-200 endemic species in Lake Victoria following intentional introduction of Nile perch (<i>Lates niloticus</i>) and Nile tilapia (<i>Oreochromis niloticus</i>). Moyle (1986) reported the dominance of many lowland rivers in the western U.S. by non-native fishes and invertebrates. | Witte et al. 1992, Moyle 1986, Miller et al. 1989 |
| | Food web disruption and loss of native mussels from zebra mussel invasion. | Whittier et al. 1995 |
| | Loss of small, soft-finned fish species from northeast U.S. lakes following predator introductions. | Whittier and Kincaid 1999 |
| | Mid-twentieth century collapse of native salmonid fisheries following colonization of the Laurentian Great Lakes by sea lamprey (<i>Petromyzon marinus</i>) and alewife (<i>Alosa pseudoharengus</i>). | Smith 1972 |

Attribute VII

| | | |
|---|---|--|
| Changes in organism condition or increase in anomalies in | Increased fish anomalies in the vicinity of toxic outfalls. | Hughes and Gammon 1987, Yoder and Rankin 1995b |
|---|---|--|

| | | |
|------------------------------------|--|--|
| response to pollution gradients | Altered blood chemistry and mortality in fish associated with wetlands that received oil sands effluent. Changes in growth, organism condition, fecundity, and feeding strategies for creek chub (<i>Semotilus atromaculatus</i>) across a variety of disturbance gradients (urbanization, agriculture, temperature). | Bendellyoung et al. 2000 Fitzgerald et al. 1999 |
|------------------------------------|--|--|

Attribute VIII

| | | |
|---|--|-----------------------|
| Ecosystem-level disruptions of functional integrity | Extinction and succession of littoral lake invertebrate species secondary to lake acidification; initially detected by temporal changes in taxonomic and density measures but followed by top-down and bottom-up effects at all trophic levels, caused by reduced nutrient cycling. A trophic cascade ultimately involved loss of fish and increased biomass of primary producers. | Appelberg et al. 1993 |
|---|--|-----------------------|

Attribute IX

| | | |
|---|---|--|
| Influence of spatial and temporal scale of disturbance on biological effects and recovery potential | Large-scale, multi-state status and trends assessments of Pacific salmon influenced the listing of the species under the Endangered Species Act. Environmental factors operating at different temporal and spatial scales influence the production and survivorship of juvenile Atlantic salmon. Past land use activity has long-term effects on aquatic biodiversity. Assessments of stream fish and benthic macroinvertebrate assemblages at state and regional scales reveal serious alterations in indicators of biological integrity. | Nehlsen et al. 1991 Poff and Huryn 1998 Harding et al., 1998 USEPA 2000 |
|---|---|--|

Attribute X

| | | |
|-----------------------|--|--|
| Ecosystem connectance | Extirpation of Pacific northwest salmon following construction of impassable dams. Extirpation of Colorado River fishes following dam construction. | Frissell 1993 Holden and Stalnaker 1975 |
|-----------------------|--|--|

TABLE 4. Functional ecological attributes or process rates and their structural indicators.

| Biotic Level | Function or Process | Structural Indicator |
|-------------------------------|---|---|
| Individual | Fecundity | Maximum individual size, number of eggs |
| | Growth & metabolism | Length/weight (condition) |
| | Morbidity | % anomalies |
| | Growth & fecundity | Density |
| | Mortality | Size/age class distribution |
| Population | Production | Biomass, standing crop, catch per unit effort |
| | Sustainability | Size/age class distribution |
| | Migration, reproduction | Presence/absence, density |
| Community or Assemblage | Production/respiration ratio, Autotrophy v. heterotrophy | Trophic guilds, indicator species |
| | Primary production | Biomass, ash free dry mass |
| Ecosystem | Connectivity | Degree of aquatic & riparian fragmentation longitudinally, vertically & horizontally; presence/absence of diadromous and potadromous species |

TABLE 5. Taxa designated as representative of Attribute I, *Historically documented, sensitive, long-lived, regionally endemic taxa*, for four different regions of the United States.

| State | Taxa Representative of Attribute I |
|------------|---|
| Maine | <p><u>Molluscs</u>: Brook floater- <i>Alasmodonta varicosa</i>; Triangle Floater- <i>Alasmodonta undulata</i>; Yellow Lampmussel- <i>Lampsilis cariosa</i></p> <p><u>Fishes</u>: Brook stickleback- <i>Culaea inconstans</i>; Swamp darter- <i>Etheostoma fusiforme</i></p> |
| Washington | <p><u>Fishes</u>: Steelhead- <i>Oncorhynchus mykiss</i></p> <p><u>Amphibians</u>: spotted frog- <i>Rana pretiosa</i></p> |
| Arizona | <p><u>Molluscs</u>: Spring snails- <i>Pyrgulopsis</i> spp.</p> <p><u>Fishes</u>: Gila trout- <i>Oncorhynchus gilae</i>; Apache trout- <i>Oncorhynchus apache</i>; Cutthroat trout (endemic strains)- <i>Oncorhynchus clarki</i></p> <p><u>Amphibians</u>: Chihuahua Leopard frog- <i>Rana chiricahuensis</i></p> |
| Kansas | <p><u>Molluscs</u>¹: Hickorynut- <i>Obovaria olivaria</i>; Black sandshell- <i>Ligumia recta</i>; Ponderous campeloma- <i>Campeloma crassulum</i></p> <p><u>Fishes</u>: Arkansas River shiner- <i>Notropis girardi</i>; Topeka shiner- <i>Notropis topeka</i>; Arkansas darter- <i>Etheostoma cragini</i>; Neosho madtom- <i>Noturus placidus</i>; Flathead chub- <i>Platygobio gracilisa</i></p> <p><u>Other Invertebrates</u>: Ringed crayfish- <i>Orconectes neglectus neglectus</i>; Plains sand burrowing mayfly- <i>Homoeoneuria ammophila</i></p> <p><u>Amphibians</u>: Plains spadefoot toad- <i>Spea bombifrons</i>; Great Plains toad- <i>Bufo cognatus</i>; Great Plains narrowmouth toad- <i>Gastrophryne olivaceae</i>; and Plains leopard frog- <i>Rana blairi</i></p> |

¹Although not truly endemic to the central plains, these regionally extirpated molluscs were widely distributed in eastern Kansas prior to the onset of intensive agriculture.

Figure Legends

Figure 1. Conceptual model relating changes in measurable ecosystem attributes to human disturbance over time (modified from Cairns et al., 1993).

Figure 2. Conceptual model depicting stages of decline in biological conditions in response to an increasing stressor gradient.

Figure 1.

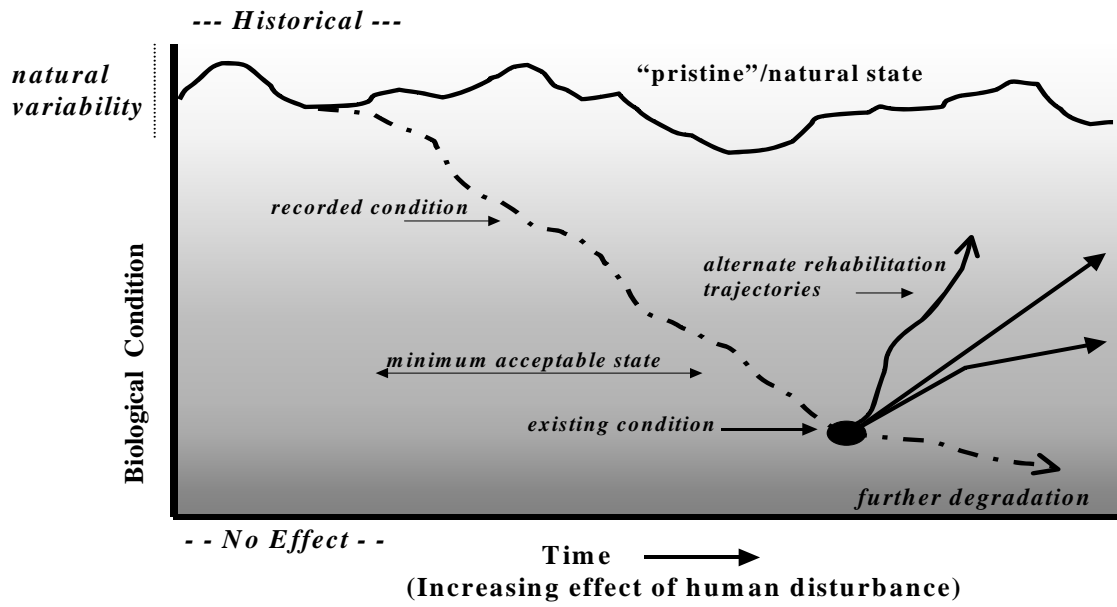


Figure 2.

