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# A classification system for the diagnostic monitoring and assessment of coral reefs

**Key words** coral reef • classification • diagnostic monitoring and assessment • index of biotic integrity

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**Abstract** A classification system for the diagnostic monitoring and assessment of coral reefs is presented. The classification system is built on an abiotic foundation for stability and to capture the prime physical forces that determine coral reef zonation. The framework contains the elements of biogeographic region, coral reef type, coral reef zone and zone modifiers. The zone modifiers are windward/leeward exposure, substrate slope angle, depth, sediment type and grain size. An analysis of existing coral reef monitoring site selection systems and various existing coral reef classification systems demonstrates the need for a special purpose classification system designed specifically for coral reef monitoring and assessment. A procedure for classifying coral reefs is presented, as are examples of classifying coral reefs. There are many advantages to the classification system. First, it is the only classification used exclusively for monitoring and assessment that uses a biogeographic component to insure realistic comparisons among large-scale environments. Second, our classification system recognizes the importance of and allows monitoring and assessment in different coral reef zones. Third, it refines the abiotic modifiers to include only those absolutely necessary to be effective. Finally, it is economical, simple and easy to use and does not require a new terminology set. The classification system for diagnostic monitoring and assessment would be a useful module to the United States National Coastal/Marine Classification Standards.

## Introduction

The purpose of this paper is to outline the crucial components of a viable classification system for diagnostic coral reef monitoring and assessment that can be applied to United States (US) coral reefs. In this process we:

- emphasize the importance of physical environment classification in any systematic program of coral reef monitoring and assessment;

- describe the important abiotic foundation of the classification system;

- present a simple but effective classification framework;

- analyze existing classification systems relative to their applicability to diagnostic monitoring and assessment; and

- demonstrate the use of the classification system.

The classification system presented is based on a review of empirical and theoretical studies of the key environmental variables in coral reef systems. The end result is a concise distillation of the key elements required for a simple and effective coral reef classification system for diagnostic monitoring and assessment. The justification for and evolution of special purpose coral reef classifications is discussed by Kulcher (1986a).

This classification system can also serve as a coral reef monitoring module for the US National Coastal/Marine Classification Standard (USNC/MCS) which is under development (Madden in prep) and uses USNC/MCS terminology where appropriate. There are several advantages to having a coral reef monitoring module in the USNC/MCS. The USNC/MCS (Madden in prep) is a broad-brush multi-purpose approach to classification. Because it is not focused on one special purpose it does not identify for the researcher the critical classification elements (independent abiotic variables little affected by humans) to successfully meet the needs for effective coral reef monitoring and assessment. But just as important, it also does not identify for the researcher the inappropriate classification elements that can corrupt comparisons (i.e., dependent variables impacted by human pollution such as; temperature, salinity and turbidity). As such, using all of the elements in the USNC/MCS will not yield an effective result for diagnostic or non-diagnostic coral reef monitoring and assessment. But to the contrary would complicate monitoring and assessment efforts, be unnecessarily expensive and time consuming and result in faulty comparisons and flawed assessments. In addition, the classification system for diagnostic monitoring and assessment picks up where the USNC/MCS leaves off, that is; at the critically important coral reef zone and zone modifier levels.

Our interest in coral reef classification stems from the need to strengthen coral reef monitoring and assessment through application of multimetric indexes such as the index of biological integrity (IBI) developed for freshwaters (Karr 1981, Karr and Chu 1999) and recently described for eelgrass (Deegan et al. 1997) and coral reef systems (Jameson et al. 1998, Jameson et al. 2001). IBI differs from traditional coral reef monitoring programs in several ways. First, multimetric indexes are based on a rigorous process of defining biological indicators (calibrated metrics) that provide clear and easily interpreted early warning signals of degradation. Second, they integrate a number of distinct measures or metrics to provide a multidimensional view of biological condition at sample sites. Finally, they are scaled against a benchmark or reference condition, the condition or character of ecologically equivalent sites with little influence from human activity (Jameson et al. 2003). Multimetric indexes such as IBI are a useful way to summarize complex information in a simple, yet easily interpreted and quantitatively robust framework.

Classification for diagnostic monitoring and assessment is important because it ensures that reference site environments are similar to monitoring site environments and that all monitoring site environments are similar to each other. Classification, before monitoring begins, also insures that reasonable comparisons are made among similar environments when data are evaluated and results reported. Proper classification is especially important for monitoring programs operating on large scales (i.e., The Global Coral Reef Monitoring Network (GCRMN), Reef Check and the Atlantic and Gulf Rapid Reef Assessment (AGRRA)), but also has relevance to small-scale local efforts (i.e., within marine parks) where varied physical environments occur. Monitoring without classifying environments can result in flawed assessments and worse, ill informed regulatory, remediation, and restoration programs.

While this paper focuses on developing a classification system for monitoring and assessment of US coral reefs using IBI metrics, the approaches discussed can also be applied to non-diagnostic monitoring programs (i.e., GCRMN, Reef Check and AGRRA) and to coral reefs outside of US jurisdiction.

Coral reefs under United States jurisdiction are defined as coral reefs in waters where any United States environmental regulations apply and does not imply that the United States federal government subsumes jurisdiction within the territorial sea.

This paper is part three of a continuing effort by the United States Environmental Protection Agency (USEPA) to establish the foundation for a biological criteria program to better protect water quality and biota in coral reefs under United States jurisdiction. Biological criteria define the desired biological condition for a water body. When adopted by states or governments, they become legally enforceable standards (narrative expressions or numerical values). Part one of this effort was a needs assessment and feasibility study (Jameson et al. 1998). Part two was a research strategy for creating coral reef IBI’s (Jameson et al. 2001). Part four outlined establishing reference conditions for coral reef diagnostic monitoring and assessment using IBI's (Jameson et al. 2003). All papers and updates on coral reef IBI research progress can be downloaded at <http://www.epa.gov/owow/oceans/coral>.

## Classification Foundation

Like a taxonomy of places, classification for diagnostic monitoring and assessment is the process of defining similar physical environment types, in our case, biogeographic regions coral reef types and coral reef zones.

Physical environmental factors and geographic characteristics (i.e., features of the continental shelf, ocean currents, and the occurrence of upwellings) play an important role in creating biogeographic regions (Sullivan Sealy and Bustamante 1999, Ekman 1967). This is the critical large-scale component of the diagnostic monitoring and assessment classification system foundation.

Abiotic parameters also form the foundation of defining the coral reef types and the very important coral reef zones of this classification system for two reasons.

(1) Physical or abiotic conditions provide the deterministic framework within which species and assemblages of species exist at a place. Whether the focus of monitoring is fish, corals, or other benthic invertebrates, the diversity of taxa varies from reef flats to reef slopes, from shallow to deepwater segments, and from windward or leeward coral reef locations. These local scale variations in the biota of reef environments are typically a function of a few characteristics of coral reef physical environments. Empirical (Adey and Burke 1977, Geister 1977, Dollar 1982, Done 1983, Veron 1995) and modeling (Graus et al. 1984, Macintyre et al. 1987, Graus and Macintyre 1989) studies demonstrate that wave and light energy are key environmental determinants of coral reef zonation. Alterations of energy input (i.e., wave conditions, wave refraction angle, and light

conditions), bathymetric setting (i.e., width of off shelf reef and depth of reef) and morphology (angle of outer fore-reef slope, height of outer ridge, height of buttress, depth of crest, depth of back-reef lagoon, height of patch reef, and widths of inner fore reef and back reef lagoon floor), working synergistically, change the magnitude and distribution of wave and light energy and thus create the zonation “fingerprint” (Fig.1) unique to a particular geographic location (Graus and Macintyre 1989).

(2) Abiotic parameters are not (or only temporarily) influenced by human impacts, biological interactions or disturbance events (such as hurricanes) and thus provide maximum stability to the classification system.

## Classification framework

The goal of classification for diagnostic monitoring and assessment is to capture the primary biogeographical and physical variables that define macro- and micro-variation in coral reef environments. To do this the framework needs the following elements.

- Biogeographic region (including latitude and longitude)
  - Coral reef type (including geographical context)
    - Coral reef zone
      - Zone modifiers (abiotic physical)

*Biogeographic region (including latitude and longitude):* The element of biogeographic region ensures we are not comparing biogeographically dissimilar fauna and flora (i.e., Central Pacific to Hawaiian or South Florida to Central Caribbean). Biogeographic regions presently used in this classification system for US coral reefs in the Gulf of Mexico, Western Atlantic and Caribbean follow those of Sullivan Sealy and Bustamante (1999) and those for the Pacific follow Ekman (1967). Research is underway to refine biogeographic regions relative to coral reefs under US jurisdiction and this will be reported in Madden (in prep). IBI calibration studies will also help validate and refine biogeographic regions.

*Coral reef type:* This element should include the type of coral reef being classified (i.e., bank, fringing, barrier) and its geographical context (i.e., continental shelf, high island, atoll,). See Madden (in prep) for standard terminology.

*Coral reef zone:* Of all the elements in the classification this is the most important because it involves the abiotic physical forces that control what types of organisms can exist in the resultant environment. This does not mean there is a need to get complicated or to reinvent the wheel. Coral reef zones include standard terms such as; channel, lagoon, reef flat, back reef, reef crest, reef slope, and reef terrace. One should avoid using overlapping zone terms alone such as fore reef that might include other zones (i.e., reef crest, reef slope and terrace). Users should also not use biotic habitat terms (i.e., *Acropora* zone) to designate the abiotic zones. To help standardize zone terminology the following references are provide for coral reefs under US jurisdiction (Table 1).

Most exiting non-diagnostic monitoring programs focus on the reef slope (Table 2). Diagnostic monitoring programs however, will be looking at human impacts across a gradient of human influence and therefore will be operating in a more diverse cross-section of the entire coral reef.

*Zone modifiers:* Abiotic zone modifiers are also critical in successful classification for diagnostic monitoring and assessment because they also influence what types of biota can survive in a particular zone. Abiotic zone modifiers should be those least affected by human influence so they can be relied upon to be relatively stable throughout time. Because the list of abiotic zone modifiers has the potential to get out of control very quickly (Table 2), we have selected a few important ones to focus on that should be sufficient to characterize coral reef zones for diagnostic monitoring and assessment. They are:

*windward exposure, leeward exposure, substrate slope angle, depth,*
*sediment type (calcareous, terrigenous, volcanic) and grain size.*

Grain size is especially important for diagnostic monitoring and assessment because the benthic macroinvertebrate IBI (Jameson et al 2001) will rely heavily on organisms whose distribution and diversity varies with grain size (i.e., amphipods).

We do not recommend using temperature, salinity, and turbidity as foundation modifiers for the classification system because they are variables that could be influenced by human pollution (unstable) and be the factors causing the negative impacts on the coral reef environment (i.e., we are looking for independent variables as modifiers). Temperature, salinity, and turbidity data should be collected as part of the monitoring program effort.

## Analysis of existing coral reef monitoring and assessment classification systems

In Table 2 we analyze existing classification systems relative to their applicability to the framework necessary for effective diagnostic monitoring and assessment. Most of the multi-purpose classification systems in Table 2 are very complicated because they are trying to fulfill many purposes.

## Classification procedure

Our goal in classifying coral reefs for diagnostic monitoring and assessment is not to create a complicated matrix of environmental parameters that will give us data to four decimal places — when we only need integer values to be effective. Ideally, the procedure should be as simple as looking at the place and integrating in some reasonable mental model fashion what is the biogeographic region and major coral reef zone of interest. The simple procedure for classifying coral reefs for diagnostic monitoring and assessment is outlined in Fig. 2.

## Classification example

Table 3 provides several examples of classifying coral reefs for diagnostic monitoring and assessment.

## Discussion

There are several advantages to this classification system for diagnostic monitoring and assessment over any others in existence today.

1. It is the only classification system used exclusively for monitoring and assessment that utilizes a biogeographic component to insure realistic comparisons between and among large-scale physical environments. We would be concerned with the validity of comparisons from existing monitoring programs that neglect this important factor specifically those analyzing data from wide geographic locations that are lumping data from different biogeographic regions. This same concern can be expressed for monitoring programs that lump data from different coral reef zones.

In addition to comparing similar coral reef zones, other standardization factors are required in legitimate comparisons. For example, one should only compare samples if sampling protocols, including both sampling technique and season, are matched (see Karr and Chu 1999 and Barbour et al. 1999 for reviews of these and related subjects).

2. This system recognizes the importance of and allows monitoring and assessment in different coral reef zones. It is not confined to just the reef slope like most other monitoring and assessment site selection systems. This flexibility in targeting is essential when trying to detect the impacts of human disturbance. For example, human impacts

may not be detectable on the offshore reef slope but are clearly evident on the near shore patch reefs.

3. While GCRMN, Reef Check and AGRRA use abiotic modifiers to varying degrees in their site selection systems, our classification system refines them to include only those absolutely necessary to be effective for diagnostic and non-diagnostic monitoring and assessment. Our classification system also strongly emphasizes their critical role in classifying similar coral reef physical environments.

4. The classification system for diagnostic monitoring and assessment is economical, simple and easy to effectively use.

5. To use this classification system does not require a new terminology set. It relies on simple standard terms found thought the literature.

*Future research needs:* Validating the Central Pacific biogeographic region described by Eckman (1967) would be an interesting and useful topic for future research. Madden (in prep) proposes using three biogeographic regions for the Central Pacific biogeographic region (Eckman 1967): NW Pacific (includes Marianas Islands and Guam); Central Pacific (includes Wake Atoll, Johnston Atoll, Kingman Reef, Palmyra Atoll, Howland Island, Baker Island, Jarvis Island) and the SW Pacific (includes American Samoa). This division is based on biotic data and not on abiotic physical data (which actually controls the biotic distribution) and also could use scientific validation.

## Conclusion

The classification system for diagnostic monitoring and assessment presented in this paper fills the need to provide a consistent mechanism to make valid comparisons among monitoring and reference sites not only for diagnostic monitoring and assessment programs but also for existing non-diagnostic programs.

All our attempts at classification for diagnostic monitoring and assessment are human constructs that help us understand a spatially and temporally varying seascape. There is not truth or absolute to this classification, or any other, because in reality, no two coral reef zones are exactly alike. Natural gradients occur between coral reef zones. Consequently, we should not always expect distinct differences, even though we seek them.

We should also guard against the impression that there is a formulaic or menu driven measurement of a few dimensions that will always yield the same truth, when in fact, we are really trying to use best professional judgment to create broad, even somewhat overlapping classes.

All classification for diagnostic monitoring and assessment does is recognize that different kinds of environments support different kinds of natural or minimally disturbed biology. The goal is to do our best to identify zones without making everyplace unique or lumping places that are too disparate in their biological context (i.e., number of taxa in standard samples). In diagnostic monitoring, want to make sure the normal values for the selected IBI metrics are not so different among sites that we have a very heterogeneous set.

Classification for monitoring and assessment should not focus on the details of what species are present but at the primary physical features that define the ecological character of the assemblage (see Premise 24, page 122 in Karr and Chu 1999). Assessments should emphasize the aspects of ecological context and structure rather than the more or less random shifts in species composition and abundance that are common even within a coral reef zone (Jameson et al. 2001).

The ultimate balance we seek in diagnostic monitoring is how little can we do to be sure of condition and cause. The key is to find out what zone is best and why, what assemblage is best and why, and if combinations of zones and assemblages provide improved understanding of coral reef condition including the all important capabilities of early warning and diagnosis of cause of impact.

**Acknowledgements** This research was funded by the United States Environmental Protection Agency under order #3W-0020-NATX to Coral Seas Inc. - Integrated Coastal Zone Management. JRK acknowledges support of the USEPA/NSF Water and Watersheds Program (Grant 825284010) and the Consortium for Risk Evaluation (CRESP) through Department of Energy Cooperative Agreement #DE-FCO1-95EW55084. We thank M Chiappone and two anonymous peer reviewers for constructive comments on the manuscript.

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**Fig. 1** Abiotic fingerprint of a Caribbean coral reef (West Reef at Discovery Bay, Jamaica) using bottom wave velocity and depth (i.e. light). Maximum depth boundaries represent greatest depths of frame construction in Caribbean reefs; minimum depth boundaries are the mean growth heights. Wave velocity boundaries are based on breaking strength measurements, occurrence of zones under known wave conditions, and the recognized sequence of zones with respect to wave energy. The maximum wave velocity boundary shown for sediment assumes a wave period of 4 s (the actual boundary varies with wave period). Mixed coral can occur at a minimum depth of 1 m in the absence of *Acropora palmata* or *A. cervicornis*. Dashed lines indicate approximate location of boundary or gradual transition between zones (from Graus et al. 1984).

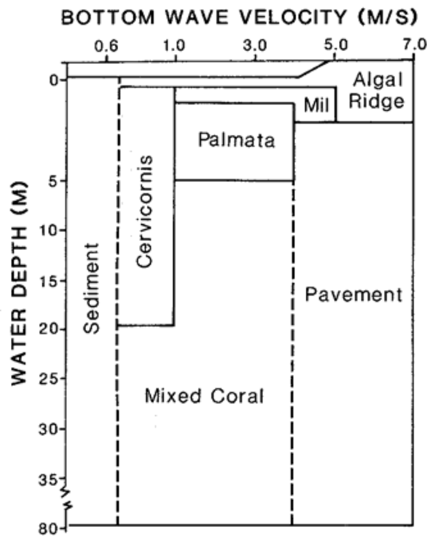

**Fig. 2** The steps in classifying coral reefs for diagnostic monitoring and assessment using indexes of biotic integrity.

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1. Define the biogeographic region using Sullivan Sealy and Bustamante (1999) or Ekman (1967) (e.g., Central Caribbean, Central Pacific)

↓

2. Determine major reef type and geographical context (e.g., high island fringing reef)

↓

3. Determine major reef zones using best professional judgement.
Be aware of other special circumstances (e.g., high reef crest)

↓

4. Determine reef zone(s) to be sampled and define appropriate sampling procedures for the IBI metric biological assemblages

↓

5. Monitor biota to evaluate current biological condition and assess divergence from expectations at minimally disturbed reference sites or using other reference condition data

↓

6. Review classification decisions. If OK, continue. If not, go back to steps 1, 2 and 3.

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**Table 1** References for standard coral reef zone terminology for a classification system for the diagnostic monitoring and assessment of coral reefs under United States jurisdiction.

| **Biogeographic Region / US Coral Reefs** | **References** |
|---|---|
| Gulf of Mexico / Flower Gardens | Bright and Pequegnat (1974) |
| South Florida/ South Florida and Florida Keys | Jaap and Hallock (1990) |
| Central Caribbean/ Puerto Rico | Rützler and Macintyre (1982)<br>Mumby and Harborne (1999)<br>Kendall et al. (2000) |
| Lesser Antilles / US Virgin Islands | Mumby and Harborne (1999)<br>Kendall et al. (2000) |
| Hawaii / Hawaiian Islands | Carpenter and Maragos (1989)<br>Holthus and Maragos (1995)<br>Maragos (in prep) |
| Central Pacific/ Wake Atoll, Johnston Atoll, Kingman Reef, Palmyra Atoll, Howland Island, Baker Island, Jarvis Island | Carpenter and Maragos (1989)<br>Holthus and Maragos (1995) |
| Central Pacific/ Marianas Islands | Randall and Holloman (1974)<br>Carpenter and Maragos (1989)<br>Holthus and Maragos (1995) |
| Central Pacific/ American Samoa | Birkeland et al. (1987)<br>Carpenter and Maragos (1989)<br>Holthus and Maragos (1995) |

**Table 2** Analysis of recent existing coral reef classification systems[1] relative to their applicability to the framework necessary for effective diagnostic monitoring and assessment.

| **Classification system by purpose and scale** | **Biogeo-graphic region** | **Coral reef type** | **Coral reef zone** | **Zone modifiers** |
|---|---|---|---|---|
| **Monitoring large-scale** | | | | |
| GCRMN[1] | | | reef slope | depth |
| Reef Check[1] | | | reef slope | depth |
| AGRRA[1] | | | reef slope | depth, windward/leeward, approximate relief, slope, size and shape of relief features |
| **Specific-purpose and large-scale** | | | | |
| Kuchler 1986 a,b; 1987 (remote sensing on Great Barrier Reef) | | | | windward/leeward, substrate type, slope, depth |
| **Multi-purpose island specific** | | | | |
| Kendall et al. 2000 (Puerto Rico & US Virgin Islands) | | | | |
| Maragos (in prep) (NW Hawaiian Islands) | | | | dredged |
| **Multi-purpose large-scale** | | | | |
| Holthus and Maragos 1995 | | | | Fringing reef: windward/leeward, reef top width, no. of passes, pass/reef top depth and width, pass/reef top % of reef perimeter, reef |

| | | | | |
|---|---|---|---|---|
| | | | | islet size, linear ocean extent, islet % of reef perimeter, no. of reef islets, reef slope, substrate type, terrace width, slope/terrace surface,<br>Barrier reef: windward/leeward, lagoon size, lagoon depth, lagoon area, lagoon no. of patch reefs |
| Mumby and Harborne 1999 | | | | spur & grove relief, forereef slope, escarpment slope, patch reef density, patch reef diffuseness, lagoon floor slope, lagoon floor depth |
| Allee et al. 2000 | | | | depth |

[1] This information is part of a monitoring site selection process not from a formal pre-monitoring coral reef classification process. Information on monitoring programs from the following sources. Global Coral Reef Monitoring Network (GCRMN): www.gcrmn.org/protocol.html, English et al. 1997, Bainbridge 1996. Reef Check: www.reefcheck.org/pubs.htm. Atlantic and Gulf Rapid Reef Assessment (AGRRA): www.coral.noaa.gov/agra/method/methodology.htm#selection.

**Table 3** Examples of classifying coral reefs for diagnostic monitoring and assessment. [1]Biogeographic elements from Sullivan Sealy and Bustamante (1999) and Eckman (1967).

| **Biogeographic region**[1] | **Coral reef type** | **Coral reef zone** | **Modifiers** |
|---|---|---|---|
| Gulf of Mexico (latitude and longitude) | Bank | Reef top | Windward exposure,<br>23-25 m depth,<br>0.3-1.6 mm sediment grain size,<br>calcareous substrate |
| South Florida (latitude and longitude) | Bank | Channel patch reefs | Windward exposure,<br>2-5 m depth,<br>0.2-1.4 mm sediment grain size,<br>calcareous substrate |
| Lesser Antilles (latitude and longitude) | High island fringing | Reef slope - outer spur & groove | Windward exposure,<br>15-25° slope,<br>9-16 m depth,<br>0.5-1.8 mm sediment grain size,<br>calcareous substrate |
| Central Pacific (latitude and longitude) | Atoll fringing | Reef flat | Leeward exposure,<br>0-1 m depth,<br>0.3-1.5 mm sediment grain size,<br>calcareous substrate |