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Water quality standards for coral reef protection

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Abstract. The U.S. Clean Water Act provides a legal framework to protect coastal biological resources such as coral reefs, mangrove forests, and seagrass meadows from the damaging effects of human activities. Even though many resources are protected under this authority, water quality standards have not been effectively applied to coral reefs. The Environmental Protection Agency is promoting biocriteria and other water quality standards through collaborative development of bioassessment procedures, indicators and monitoring strategies. To support regulatory action, bioassessment indicators must be biologically meaningful, relevant to management, responsive to human disturbance, and relatively immune to natural variability. A rapid bioassessment protocol for reef-building stony corals was developed and tested for regulatory applicability. Preliminary testing in the Florida Keys found indicators had sufficient precision and provided information relevant to coral reef management. Sensitivity to human disturbance was demonstrated in the U.S. Virgin Islands for five of eight indicators tested. Once established, monitoring programs using these indicators can provide valuable, long-term records of coral condition and regulatory compliance.

Key words: Clean Water Act, biocriteria, coral reefs, water quality standards

Introduction

Coral reefs worldwide suffer adverse effects from human activities (Lough, 2008; Knowlton and Jackson, 2008; Mora, 2008; Sandin et al. 2008). Marine Protected Areas (MPAs) are widely used in coral reef conservation to restrict fishing, diving and boating in selected areas, but cannot protect coral reefs from the many other human activities that degrade coastal zones from upstream watersheds (pollutant discharge, urban and industrial activity, agriculture) and outside MPA boundaries (dredging, dumping, fishing).

Fortunately, the Clean Water Act (CWA) provides a legal and regulatory framework to protect aquatic resources, including coral reefs, mangrove forests, wetlands and seagrasses in U.S. territorial waters. The CWA mandates that states and territories protect and restore the chemical, physical, and biological integrity of the Nation's waters (CWA Section 101 (a)). Protection extends to all territorial waters within three miles of shore, not just those within MPA boundaries, and regulatory responses to impairment can influence a range of management actions and decisions in both the coastal zone and watershed (e.g., fishery restrictions, land use allocations, building permits, effluent discharge permits). This comprehensive scope makes the CWA a powerful tool, having the potential to integrate conservation efforts across municipalities, coastal zones and landscapes. Moreover, designated waterbody uses (what to protect) and water quality standards (the level of protection) are state decisions, and therefore represent regional cultural and socioeconomic values.

The U.S. Environmental Protection Agency (EPA) is promoting development and implementation of coral reef biological criteria (biocriteria) as the most direct application of the CWA for protection and restoration of coral reefs (see Bradley et al. 2008a). The CWA requires that States and Territories define water quality standards for all waters. Water quality standards include 1) designated uses reflecting societal goals for the water body, 2) criteria to achieve the designated uses, and 3) antidegradation policies to prevent deterioration of high-quality waters. Criteria define the thresholds (expectations) for biological, chemical, or physical indicators of resource condition and may be described in narrative or numeric terms. When biological criteria are adopted, they are legally binding—carrying both an obligation and authority to maintain the specified biological integrity. If a waterbody fails to meet the criteria, then it fails to support the designated uses and is listed as impaired in the CWA Section 303(d) report to Congress. Cause of impairment must be determined and restorative measures initiated.

Biocriteria have been broadly applied in the protection of streams, lakes, and estuaries (EPA 2002), but not coral reefs and other nearshore habitats. An important advantage of biological over physical and chemical water quality standards is that living organisms integrate the effects of multiple stressors through time, providing a reliable indicator of ecological condition (Jameson et al. 2001) rather than independent snapshots of single stressors. Biological endpoints are also transparent to stakeholders and can guide and support management decisions. Moreover, bioassessments and biological endpoints are directly responsive to the fundamental purpose of the CWA—protection of valued aquatic resources. Bioassessments incorporated into a long-term monitoring program could simultaneously provide diagnostic, management and regulatory information.

The lack of coral reef biocriteria in U.S. jurisdictions prompted EPA to initiate a collaborative program to foster development of water quality standards specifically to protect coral reef communities (Bradley et al. 2008b). A first objective was to develop bioassessment indicators and protocols suitable for regulatory application. Legally defensible monitoring programs and indicators must be scientifically sound, biologically meaningful, relevant to management, predictably responsive to human disturbance and relatively immune to natural variability. These factors are examined here for a recently introduced assessment protocol for stony corals.

The *Stony Coral Rapid Bioassessment Protocol* (RBP; Fisher 2007) was developed to capture both colony and surface area attributes of stony corals. Stony corals directly provide valuable ecosystem services (e.g., shoreline protection, community habitat) and form the infrastructure of most coral reefs. The potential of the protocol for development of biocriteria was examined in studies performed in the Florida Keys and U.S. Virgin Islands.

Material and Methods

The RBP consists of three simple underwater measurements; coral identification, coral size (height, diameter and width), and percent living tissue (Fisher 2007). Because most colonies were hemispheric, the average radius of each colony was converted to three-dimensional colony surface area (SA) using a hemispheric surrogate ($SA=2\pi r^2$). Colonies of the most abundant species in Florida and the Caribbean are hemisphere or dome-shaped, and this surrogate was found to estimate surface areas within 17% of actual (Courtney et al. 2007). Different coral species would require different geometric surrogates. Indicators (Table 1) included taxa richness, colony density and calculations of average colony surface area, total surface area (TSA), average % live tissue, live surface area (LSA), % live surface area (LSA/TSA*100) and the coefficient of variation for average colony surface area (CSA-CV) Indicators reflect both surface area (e.g., coral cover) and colony characteristics (e.g., density, size) of corals.

Two pilot studies were performed in the Florida Keys to assess the capacity of RBP indicators to detect spatial change and to evaluate the potential utility for management decisions. Studies at St. Croix, U.S. Virgin Islands further examined the potential of RBP indicators to differentiate human disturbance from natural variability. A survey was performed at stations located across a strong human disturbance gradient (industrial ship channel) on the southern shore of St. Croix. Indicators were tested for correlation with distance away from the center of the human disturbance.

Indicators of Physical and Biological Condition
Colony density: *number of colonies per m^2 sea floor*
Species (taxa) richness: *# species occurring in a defined region*
Colony surface area (CSA): *surface area (3D) of an entire colony*
Total surface area (TSA) = *Σ CSA (m^2)*
Average colony surface area (AvCSA) = *TSA/ #colonies (m^2)*
Colony size coefficient of variation (CSA-CV)=*standard deviation CSA/mean CSA*
3D Total Coral Cover (TC) = *TSA/ m^2 sea floor*
Percent Live Tissue (%LT): *percent live tissue on a coral colony*
Average Percent Live Tissue (Av%LT) = *Σ %LT/ #colonies*
[2]**Colony Live Surface Area**: *surface area (3D) of live coral tissue on an entire colony (m^2)*
Live surface area (LSA) = *Σ colony live surface areas (m^2)*
3D Live Coral Cover (LC) = *LSA/ m^2 sea floor*
Percent Live Surface Area (%LSA) = *[LSA/TSA]*100*

Table 1: Selected indicators from observations and calculations of stony corals using the Stony Coral Rapid Bioassessment Protocol (Fisher 2007).

Results

In all three studies, indicators detected differences between stations and were determined to have sufficient precision for most monitoring programs (Fore et al. 2006). In addition, five of eight indicators tested across a human disturbance gradient at St. Croix were positively correlated with distance from the center of the disturbance zone (for example, see Fig. 1). Indicators that were responsive to human disturbance were taxon richness, AvCSA, CSA-CV, TSA and LSA. Coral density tracked distance from disturbance but the correlation was not significant. Because of small colonies with high %LT in the disturbance zone, associations of average %LT and %LSA were negative (Fisher et al. 2008).

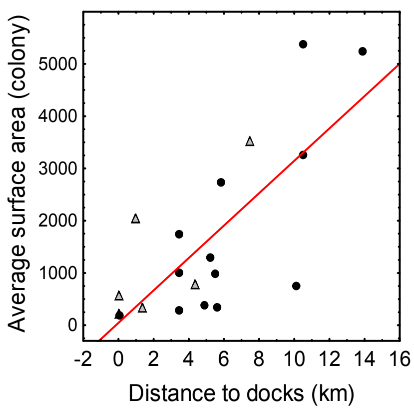

Figure 1. Relationship of colony surface area (AvCSA) with distance from commercial docks on the south side of St. Croix, USVI (from Fig. 2 of Fisher et al. 2008). This is one of five indicators that showed a predictable response from human disturbance. Triangles represent stations west of the commercial docks, circles are stations east of the docks (n = 19 stations).

In each survey, small colonies were more abundant than large colonies, but the greatest LSA was provided by mid-sized colonies (e.g., Fig. 2). Percent live tissue (%LT) declined with colony size for all species, but in the Florida Keys dropped dramatically for medium and large Elkhorn (*Acropora. palmata*) colonies (Fig. 3). Elkhorn corals provided the most reef habitat (TSA) at the Florida Keys stations, but exhibited the poorest health (LSA/TSA) relative to other species (Fig. 4). This condition was most conspicuous at a single reef, Sand Key, where numerous large *A. palmata* were devoid of live tissue (data not shown). Population structure (colony size-frequency) varied across regions for different species (Fore et al. 2006), and this was particularly evident for species at St. Croix where strong recruitment (abundant small colonies) was found at some locations and not at others (e.g., Fig. 5).

Discussion

Indicators generated by the *Stony Coral Rapid Bioassessment Protocol* (RBP) should be considered further as potential metrics in a biocriteria program. The procedures are straight-forward, inexpensive and easily measured by coral reef biologists; the indicators demonstrated sufficient statistical power to monitor for trend and detected a consistent and logical response to human disturbance over natural variability. Further, the indicators are biologically meaningful, easily interpreted by non-scientists and provide information relevant to resource management.

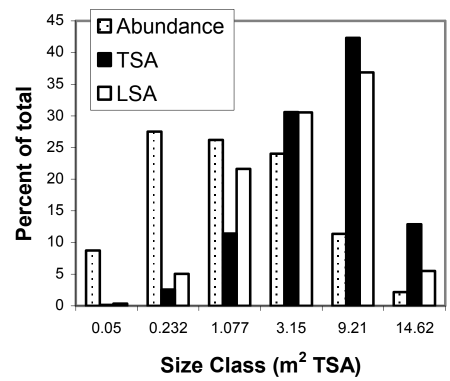

Figure 2. Relative size-class distribution of abundance (stippled bar), total surface area (TSA; dark bar) and live surface area (LSA; white bar) for *Acropora palmata* found at stations in the Florida Keys.

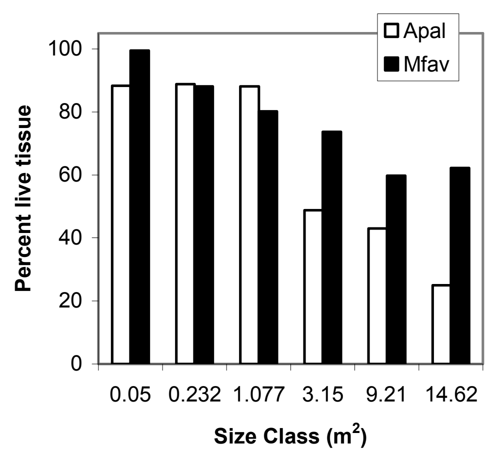

Figure 3. Comparison of the proportion of live tissue on *Montastraea faveolata* (Mfav) colonies and *Acropora palmata* (Apal) colonies relative to the size of the colonies. Large *A. palmata* had lower %LT than large *M. faveolata*.

A significant requirement for a regulatory bioindicator is predictable responses to human disturbance. It is expected that corals respond to chronically poor environmental conditions with decreasing taxon richness, size and health. In the St. Croix study, several indicators for these attributes declined consistently with distance from the zone of human disturbance. This pattern was recorded at different depths and reef habitats, signifying that the indicators were relatively immune to changes in microhabitat (Fisher et al. 2008). Although this may not always be the case, robust indicators can overcome the need for classification (sorting reefs by habitat type) which simplifies survey designs and reduces the number of stations that must be surveyed.

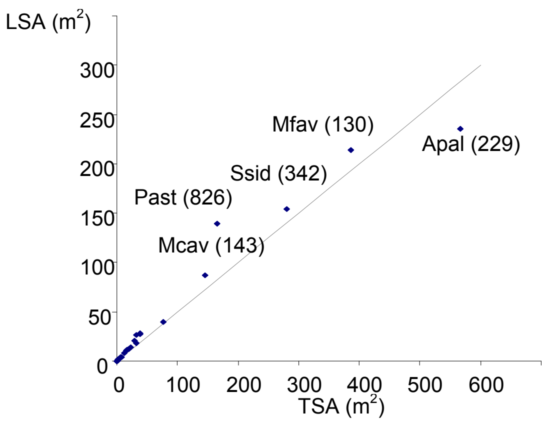

Figure 4. Comparison among coral species of live surface area (LSA; m^2) and total surface area (TSA; m^2) recorded for all colonies found at 29 stations in the Florida Keys (Mcav-*Montastraea cavernosa*; Past-*Porites astreoides*; Ssid-*Siderastrea siderea*; Mfav-*M. faveolata*; Apal-*Acropora palmata*. Colony numbers for each species are in parentheses and the dotted line represents 50%LSA.

Resource managers often focus on the condition of stony corals because they form the infrastructure of the reef and directly provide ecosystem services (e.g., shoreline protection, biological diversity, fishery harvests, and tourism). Stony corals are therefore appropriate for regulatory bioassessment. Stony coral condition has been quantified many different ways, but the RBP is unique in providing both colony and surface area data—each bearing a different subset of relevant management information. For example, the RBP includes measurements to estimate colony size, providing information on reef structural complexity, population structure and even historical condition. Likewise, the RBP includes estimates of live and total surface area, which can be used to characterize colony health and potential for growth and reproduction. The two approaches can even be combined to illustrate otherwise undocumented characteristics, such as size-related health (Fig. 3).

Colony size is sometimes ignored in coral monitoring programs, even though size provides highly relevant management information. For example, size can be used to demonstrate the size classes and species with the greatest physical capacity for growth and reproduction. In an example from the Florida Keys survey (Fig. 2), medium-sized colonies had higher LSA than small or large colonies. Areas with medium sized colonies might be expected to recover more quickly (resilience) from a bleaching event. A region with large colonies (even large, dead colonies) indicates that historic environmental conditions were capable of supporting vigorous or prolonged coral growth. A region with small colonies and low abundance may have experienced more persistent, chronic stresses. Presence of large colonies with low proportions of live tissue could indicate a region with historically good environmental conditions that suffered some catastrophic event, such as a hurricane or massive bleaching. A likely example of this was found for *Acropora palmata* at Florida Keys, a situation that was previously noted by Fisher et al. (2007). Large *A. palmata* colonies exhibited much lower %LT than large colonies of other coral species (such as *Montastraea faveolata*; Fig. 3), indicating differential sensitivity to the stressor. Smaller colonies exhibited high %LT, indicating a return to pre-event conditions for newly recruited colonies.

The plight of *A. palmata* colonies in Florida Keys was also evident—on average, colonies had less than 50% live surface area (LSA/TSA; Fig. 4). This is particularly important for resource management, not only because *A. palmata* are listed as threatened species, but also because they likely contribute more than any other species to shoreline protection, community habitat, biodiversity and tourism. Other species (e.g., *M. faveolata*) have better health but with lower TSA do not contribute as many services. Further, *A. palmata* may be critical to reef sustainability. Done (1997) claims that reef sustainability is driven by two key variables, reef framework and reef-building capacity. Elkhorn corals have already lost reef-building capacity (%LSA) and, with eventual deterioration, will contribute less and less to reef framework (TSA).

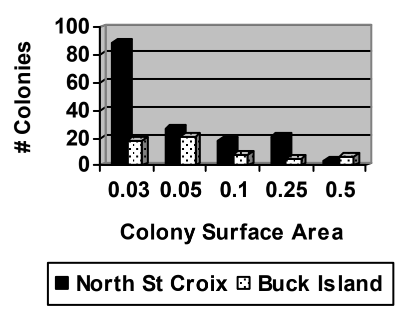

Figure 5. Number of colonies by size class (CSA; m^2) for *Diploria strigosa* from the northern shore of St. Croix (U.S. Virgin Islands) and nearby Buck Island.

Colony size can also used to compare population structure (size-frequency), which identifies populations that have high and low relative recruitment (Fig. 5). Study of population structure over time provides essential information on population dynamics (Bak and Meesters 1998). Colony size (AvCSA) and colony size heterogeneity (CSA-CV) were among those indicators responsive to human disturbance—both were lower for stations near the center of disturbance (Fisher et al. 2008; Fig. 5). Chronic human disturbance (e.g., pollution, physical damage, overfishing) may not always inhibit coral recruitment, but poor environmental conditions will likely lead to reduced growth rates and shorter life spans.

The RBP indicators exhibited significant potential for monitoring programs, regulatory standards and management utility. Although application to other locations and environments is needed, these studies complete a first step toward development of tools for coral reef biocriteria.

Since the 1980s, there has been growing recognition that water quality standards based on chemical criteria alone cannot protect biological resources (Karr 1991). This has stimulated efforts to develop biological assessment methods and to implement biocriteria. Many states and territories now fulfill the regulatory requirements of the CWA to document the condition of streams, lakes, and estuaries through local and even regional assessments of fish, macroinvertebrates, and algae (EPA 2002). Similar programs for coral reefs can be developed and implemented to provide useful management information and long-term records of coral condition and regulatory compliance.

Whereas global climate change is a major threat (Hoegh-Guldberg et al. 2007), efforts must continue to protect coral reefs from local stressors originating in the watershed and coastal zone. This compels use of the most powerful regulatory tools available. The Clean Water Act provides U.S. states and territories the legal framework and regulatory authority to designate waterbody uses specific to coral reef resources, to track status and trends using biological indicators, and to identify impaired waterbodies. Ultimately, the CWA has the capacity to trigger restrictions on diverse human behaviors that could physically damage or send toxics, nutrients, sediment, and pathogens into coral environments. The CWA is a potent regulatory tool with an expressly defined purpose—to protect aquatic life. With defensible scientific underpinnings, the CWA should be at the forefront of U.S. coral reef protection.

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