Development of Biological Criteria for Coral Reef Ecosystem Assessment

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CHAPTER 1
Introduction

1.1 PURPOSE OF THIS PAPER

The purpose of this paper is to provide the United States Environmental Protection Agency (EPA) with advice on the feasibility of establishing biological criteria for assessing coral reef ecosystems. Following up on the conclusions and next steps presented in: *A Coral Reef Symposium on Practical, Reliable, Low Cost Monitoring Methods for Assessing the Biota and Habitat Conditions of Coral Reefs* (Crosby et al. 1996), we address the following questions.

- Does sufficient need exist to justify preparation of a guidance document on the development of coral reef ecosystem biocriteria?
- Does sufficient information currently exist to draft this guidance?
- What data, research and/or projects are needed to facilitate development of such a guidance document?

Because of the interconnections which can develop between coral reefs, seagrass beds and mangrove forests, these ecosystems are considered one for the purposes of coral reef ecosystem bioassessment and biocriteria development described here. (If future assessment shows that it is not feasible to combine these habitats for the purpose of biocriteria development, then the definition of coral reef ecosystem will be changed accordingly.)

The biogeographic focus of this paper is coral reef ecosystems under U.S. jurisdiction. Coral reef ecosystems under United States jurisdiction are defined as ecosystems 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.

Table 1.1 lists those coral reef ecosystems under US jurisdiction (see Figures 1 and 2 for geographic locations). The coral reef ecosystems of the Florida Reef Tract, the Flower Garden Banks in the Gulf of Mexico, and Fagatele Bay, American Samoa receive some degree of protection as National Marine Sanctuaries.

Table 1.1: Coral reef ecosystems under United States jurisdiction.

Western Atlantic	**Gulf of Mexico**	**Caribbean**	**Pacific**
Florida Reef Tract	Flower Gardens Banks	Puerto Rico	Hawaiian Islands
		US Virgin Islands	Line Islands - Palmyra Island, Kingman Reef, Johnson Atoll, Howland Island, Baker Island, Jarvis Island
			American Samoa

			Wake Island
			Mariana Islands - 14 islands including Guam

Figure 1. Coral reef ecosystems under United States jurisdiction in the western Atlantic Ocean, Gulf of Mexico and Caribbean Sea are found around: the Florida Reef Tract; Flower Gardens Banks; Puerto Rico; and the U.S. Virgin Islands.

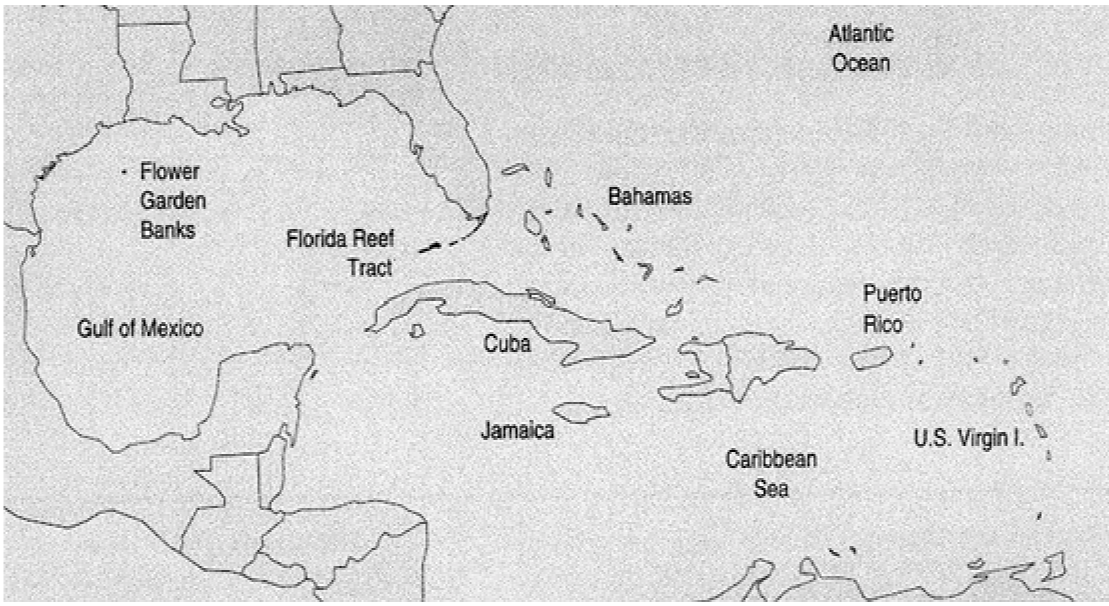
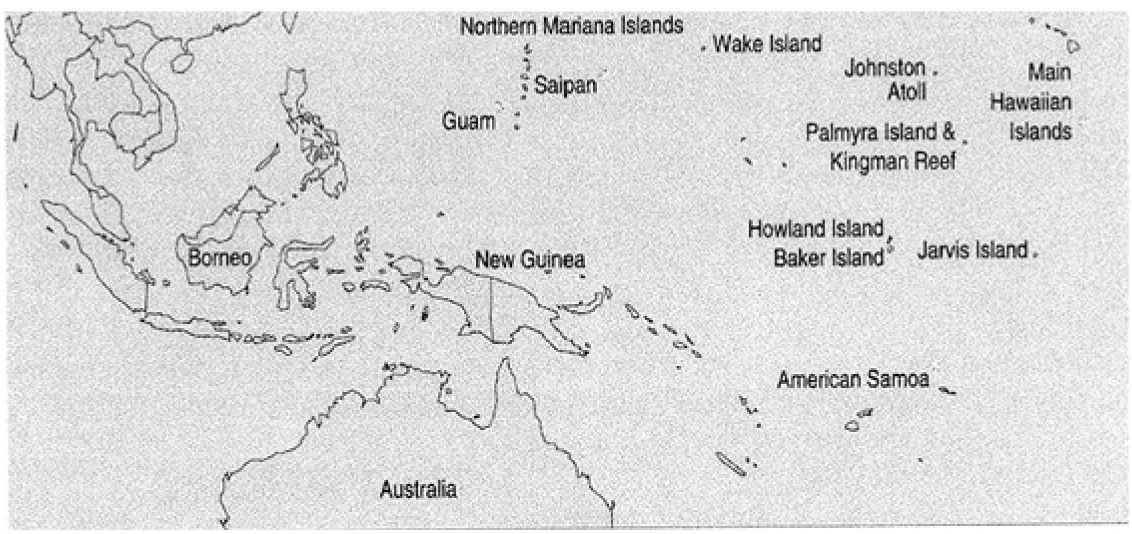


Figure 2. Coral reef ecosystems under United States jurisdiction in the Pacific Ocean are found around: the northwest and main Hawaiian Islands; the Line Islands including Palmyra Island, Kingman Reef, Johnston Atoll, Howland Island, Baker Island, and Jarvis Island; American Samoa; Wake Island; and the 14 Mariana Islands including Guam.



1.2 WHAT ARE BIOLOGICAL CRITERIA

Biological criteria are narrative expressions or numerical values that describe the biological integrity of aquatic communities inhabiting waters of a given designated aquatic life use (USEPA 1990a). Numeric biological criteria for fish and invertebrates have been adopted by the state of Ohio to evaluate the relative biological integrity of streams and small rivers. In Maine, narrative biocriteria have been developed for inland waters. Florida and California are in the early stages of developing biocriteria that will include coastal waters.

Biological assessment of water bodies is predicated on our ability to define, measure, and compare the relative biological integrity between similar systems. Biological integrity is the condition of the aquatic community inhabiting unimpaired (or minimally impaired) water bodies of a specified habitat as measured by community structure and function (USEPA 1990a). Community structure and function are the biological measures chosen for bioassessment, consisting primarily of measures of species richness, trophic diversity (relative numbers of herbivores and top carnivores), and indicator species. Unimpaired water bodies form the basis for defining reference conditions for biological criteria. When unimpaired water bodies do not exist within a region, an operational definition of unimpaired can be developed from a combination of minimally impaired coastal waters, historical information, and professional judgment.

Biocriteria measure the relative condition of a given water resource based on the investigation of the health and diversity of its resident biota when compared, in part, to similar reference waterbodies known to be unimpaired or minimally impaired by human activities. Impairment of the water body is judged by its departure from the biocriteria. Biological criteria are, in effect, a practical approach to establishing management goals designed to protect or restore biological integrity. If these criteria are included in state law they can be incorporated in State Water Quality Standards as enforceable regulations over point and nonpoint source discharges.

Below is a simplified diagram outlining the bioassessment process where biocriteria are used as the standard of reference.

Site Monitoring Data

v

converted to

v

Biological Indices

v

compared to

v

Minimally Impaired Reference Site-Supported Biocriteria

An example of a biocriterion would be as follows. A biocriterion for "Class A" coral reef sites off the Florida Keys might be "a benthic index greater than the 25th percentile of least-impaired reference conditions. " The "Class A" site would be rated impaired if its benthic index fell below the 25th percentile of the "Class A" reference condition. (Note: "Class A" is an arbitrary name used in this example for a particular coral reef habitat type developed during the habitat classification steps (see 1.3.2) in the biocriteria development process.)

The recognition that chemical water quality analyses do not adequately predict or reflect the condition of all aquatic resources has led to the development of measures of biological integrity expressed by biological criteria. Biological surveys, criteria, and assessments complement physical and chemical assessments of water quality by reflecting the cumulative effects of human activities on a water body including the possible causes of these effects. The biological approach is best used for detecting generalized and non-specific impairments to biological integrity, and for assessing the severity of those impairments. Then, chemical and toxicity tests, and more refined habitat assessments, can be used to identify probable causes and their sources, and to suggest corrective measures.

This process is essential to comply with the intent and purpose of the Clean Water Act; its primary objective, stated in Section 101 (a), is to "restore and maintain the chemical, physical, and biological integrity of the Nation's waters."

Biocriteria can be developed from reasonable expectations for the locality based on: historical data; reference conditions; empirical models; and the consensus judgement of regional experts. The reference condition component of biocriteria requires minimally impaired reference sites against which the study area may be compared. Minimally impaired sites are not necessarily pristine; they must, however, exhibit minimal influence by man's activities relative to the overall region of study. They should as much as possible approximate ecological integrity, i.e. the condition of an unimpaired ecosystem as measured by combined chemical, physical (including habitat) and biological attributes.

Biological criteria typically include the condition of aquatic communities at designated reference sites as an important component. The conditions of aquatic life found at these sites are used to help detect both the causes and levels of risk to biological integrity at other sites of that type in a region. Reference sites are used to determine an overall reference condition for waters of a certain type within a region. In keeping with the policy of not degrading the resource, the interim reference conditions - like the criteria they help define - are expected to be upgraded with each improvement to the water resource. It is important that biological criteria not be based on data derived from degraded reference sites. In fact, a concerted effort should be made by States and other jurisdictions to preserve the quality of designated reference sites by setting those areas aside in sanctuaries or parks or by inclusion in use protection programs so that continuity of the biocriteria data base can be maintained.

To develop a biocriteria program requires a rigorous and consistent data gathering process. Four increasingly refined levels or "tiers" of data collection and analysis that the resource manager may use in developing a biocriteria program are described below. The tiers are sequential and cumulative in nature and each progressive tier provides more information and greater decision making confidence to the manager than the last, albeit at a greater expense in time, supplies, and manpower. Briefly they are as follows:

1.2.1 Assessment Tiers

Biological surveys of coral reef ecosystems can be implemented in several tiers, ranging from a simple and inexpensive screening to detailed field sampling, analysis, and assessment. Each integrated tier includes both biological and habitat components. Higher tiers require successively more effort and yield more detailed information on specific biotic assemblages and potential stresses on the system. Higher tiers reflect higher quality information and reduced uncertainty in the final assessment (sensu Costanza et al. 1992). The tiered approach gives agencies flexibility in planning and implementing biological surveys. A desktop screening and three field survey tiers are described below.

Tier 0 is a desktop screening assessment that consists of compiling documented information for the coral reef ecosystems of concern through a literature search and sending survey questionnaires to local experts. No field observations are made at this assessment level. Desktop screening should precede any of the three subsequent tiers. Its purpose is to support the planning for monitoring and more detailed assessments. Information to be compiled in Tier 0 includes area and geomorphometric classification; habitat type; watershed land use; population density; NPDES discharges; water quality data (i.e., salinity, temperature, DO, pH, turbidity); biological assemblage data; and water column and bottom characteristics.

Tier 1 is the least complex of the survey approaches. It consists of a one-time visit to sites during a suitable, predetermined index period to collect biological and habitat data using standardized methods. The focus of this tier is on developing screening or survey information. These variables include a rudimentary identification of organisms (i.e., benthos, fish, macrophytes, or phytoplankton), water column characteristics (i.e., salinity, temperature, DO, pH, Secchi depth and/or turbidity, water depth), and bottom characteristics (i.e., grain size, total volatile solids, and sediment toxicity). States may choose some variation of this list depending on regional characteristics and resources. Evaluation of the data collected, as well as historical data for the area, leads to an initial classification of sites and identification of candidate reference sites.

Tier 2 is more complex. A higher level of detail is incorporated into the standardized biological survey methods and multiple visits to the site are made to address temporal variability and seasonality. Another assemblage (epifauna) could be selected in addition to those listed above. Water column nutrient measurements are added to the Tier 1 water column characteristics. More detailed grain size measurements, plus total organic carbon, are added to the bottom characteristics. The data collected in this tier will allow the development of preliminary biocriteria.

Tier 3 is the most rigorous survey tier. It includes multiple site visits to account for seasonal variations in the selected coral reef ecosystem biological assemblages and should incorporate supplemental studies which might be necessary for diagnostic assessment of the potential causes of observed impairments. This tier adds water column pesticides and metals measurements, plus full grain size characterization, and measurement of acid volatile sulfides and sediment contaminants. This tier also allows the resource agency to develop a database sufficient to support resource management activities to reduce the identified impairments and to develop and refine biocriteria.

1.3 THE BIOCRITERIA PROCESS

Development of biocriteria depends on the premise that population and condition parameters of coral reef biota (quantified as metrics or indexes which measure attributes of ecological structure and function) provide a sensitive screening tool for assessing the condition of a coral reef ecosystem. Once biocriteria are developed, based in part on minimally-impaired reference conditions, sites are evaluated to determine how well they measure up against the criteria. The greater the discrepancy, the greater the potential impairment of the water resource. The biocriteria should be carefully developed to closely represent the natural biota, provide the sensitivity to identify marginally disturbed sites, protect areas against further degradation and demonstrate the need for restoration of degraded sites. Well-written biocriteria are not set so high that sites that have reached their full potential (i.e., ecological, tourism, productivity, etc.) are considered as failing to meet the criteria, nor so low that unacceptably impaired sites are rated as meeting them. Biocriteria should be: based on sound scientific principles; quantifiable; and written to protect or enhance the designated use of the area. To account for natural variability in a healthy environment, the criterion should be designed to accommodate seasonality and should be defined as a range, often represented graphically as box plots, rather than as a discrete value.

1.3.1 Characteristics Of Effective Biocriteria

Generally, effective well-written biocriteria share the following common characteristics:

- provide for scientifically sound, cost-effective evaluations;
- protect sensitive biological values;
- protect healthy, natural aquatic communities;
- support and strive for protection of chemical, physical, and biological integrity;
- may include specific characteristics required for attainment of designated use;
- are clearly written and easily understood;
- adhere to the philosophy and policy of nondegradation of water resource quality; and
- are defensible in a court of law.

The establishment of formal coral reef ecosystem biocriteria warrants careful consideration of planning, management, and regulatory goals and the best attainable condition at a site. Stringent criteria that are unlikely to be achieved serve little purpose. Similarly, biocriteria that support a degraded biological condition defeat the intent of both the biocriteria process and the Clean Water Act. Balanced biocriteria will allow multiple uses to be considered so that any conflicting uses are evaluated at the outset.

1.3.2 Development Of Coral Reef Ecosystem Biocriteria

The use of multiple measures, or metrics, to develop biocriteria is a systematic process involving discrete steps. The process includes the following steps.

Step 1 - Preliminary Classification Of The Coral Reef Ecosystems Under Consideration And The Selection Of Reference Sites

The classification entails the division of the coral reef ecosystems into classes or groups based on physical and geographic characteristics not subject to human perturbation. The intent of classification is to identify the smallest number of classes which, under ideal conditions, would represent comparable biological communities. A set of multiple reference sites are then selected from within each coral reef ecosystem class. The reference sites are those least impaired by human influence and are characteristic of the biological community represented by that particular class. For better statistical power, each class should have a minimum of 5 to 10 reference sites from which the biocriteria are to be developed for that particular class.

Step 2 - Biological Survey

Both the biotic and physical habitat characteristics are surveyed using standardized methods within each coral reef ecosystem classification. To develop the discriminatory power of the metrics within a class, the survey should include both impaired and minimally impaired sites, and should sample two or more biological assemblages (e.g., infauna, fish, epifauna, macrophytes, plankton). Expanding survey tiers (outlined above) offer increasing refinement and complexity of the survey effort from the number of individuals and biological assemblages sampled, to the taxonomic level of identification, the extent of the physical environment sampled, and the number of sample replicates taken. Each tier represents a greater investment of resources over lower tiers, and a greater level of resolution.

Step 3 - Final Classification

The preliminary coral reef ecosystem classification is tested with the biological data to determine whether it consistently reflects the biological communities. If necessary, the classification is revised. Seasonal and spatial variability in biological data are accommodated by using measures of central tendency and variability, and by indexing the sampling period to one or two seasons (index period sampling). Successful classification will result in less variation within a class, leading to more refined characterization of the reference condition and, therefore, to criteria with better resolution for detecting impairment.

Step 4 - Metric Evaluation And Index Development

Potential metrics which have ecological relevance are identified and tested in this step. These measures should reflect biological properties which are shown to be sensitive to environmental impairment such as richness, diversity and dominance indexes, biomass and mean individual size measurements, trophic shifts, health indexes, abundance proportions of taxonomic groups, and the presence or dominance of tolerant (opportunistic) and sensitive species. Metrics are then evaluated for their ability to differentiate between impaired and minimally impaired sites. Values from various scales of measurements are transformed to scores, which are normally incorporated into an index, such as the Chesapeake Bay Estuarine Index of Biotic Integrity (IBI). Metrics may also be used individually as indicators of biological condition in the overall assessment, after they have been reevaluated using the new data set.

Step 5 - Biocriteria Development

Biocriteria are formulated in part from the metrics and index values developed from the population of reference sites for a given coral reef ecosystem class and are adjusted for aquatic life uses. Other elements of biocriteria are historical information, the consensus opinion of objective regional experts, and in some instances, empirical model results. Each class requires a separate reference characterization (hence, separate reference sites) and separate biocriteria. The reference condition element of biocriteria may be based on a single aggregated index or established for several biological metrics. For example, a biocriterion for "Class B" coral reef sites might be "a planktonic index greater than the 50th percentile of least-impaired reference conditions." A "Class B" site would be rated impaired if its planktonic index fell below the 50th percentile of the "Class B" reference condition.

Step 6 - Implementation Of Monitoring And Assessment Program

An operational monitoring and assessment program serves two primary purposes:

- first, it assesses the potentially impaired test sites; and
- secondly, continued monitoring of selected reference sites helps to determine seasonal and annual variability and trends.

Step 7 - Protective And Remedial Management Action

Where problems have been identified through this effort, land use changes, discharge reduction, pollution abatement, and resource use adjustment can be part of the management response, both to improve degraded areas and to protect exceptional minimally impaired sites from future damage.

Step 8 - Continual Monitoring And Periodic Reviews

The biocriteria-biomonitoring effort progressively improves coral reef ecosystem water resources by cycling back through the sequence to refine the classification, biocriteria, and protection or remediation techniques.

In practice, the biocriteria process involves careful planning; selection of appropriate measurements; detailed sampling design; consistent and reliable survey techniques; prudent data assessment; and responsible application of the biocriteria to protect the water resource.

1.3.3 Advantages Of Bioassessment And Biocriteria

Bioassessment is intended to detect sensitive biological responses to pollution and perturbation. Routine coral reef ecosystem water quality monitoring may not detect effects of, for example, chronic low level nutrient enrichment or ephemeral pollution events (e.g., acidic episodes, spills, short-lived toxicants and pesticides, short-term sediment loading). Bioassessment, by monitoring organisms that integrate the effects of environmental changes, can, in time, detect effects of low level contamination and ephemeral events on the biota.

Bioassessment, coupled with coral reef ecosystem habitat assessment, helps identify probable causes of impairment not detected by physical and chemical water quality analyses alone, such as nonpoint source pollution and contamination, erosion, or poor land use practices. The detection of water resource impairment, accomplished by comparing biological assessment results to the biological criteria, leads to more definitive chemical testing and investigations which should reveal the cause of the degradation. This, in turn, should prompt regulatory and other management action to alleviate the problem. Continued biological monitoring, with the data collected compared to the criteria, will determine the relative success of the coral reef ecosystem management efforts.

1.3.4 Program Interdependence

It should be readily evident from the applications described above that physical, chemical, and biological surveys and monitoring (repetitive surveys of the same area) and biological criteria are interrelated in the coral reef ecosystem water resource management process. In this continually cycling process, monitoring provides the information necessary to identify problems and to establish biocriteria for the decision making, management planning, and implementation necessary to respond appropriately. Continued monitoring then reveals the relative success of the effort by comparing the new results to those criteria again. At this point the criteria or the management plan may be positively adjusted as needed and the cycle repeats. Ideally, the habitat quality, water quality and productivity of the monitored coral reef ecosystems improve with each cycle.

1.3.5 Implementing Coral Reef Ecosystem Biological Criteria

Implementing biocriteria requires an established and standardized methodology for coral reef ecosystem biological assessment adjusted to regional or state conditions. Hence, guidance for state and regional development of biocriteria has two elements which would be described in the biological criteria technical guidance documents.

- Bioassessment Protocols are methods used to assess the status and trends of coral reef ecosystems. Guidance documents for bioassessment contain suggested methods and protocols for establishing monitoring programs that use biological assessment.

- Biocriteria Guidance assists states in establishing biological criteria for coral reef ecosystems. Biocriteria are a series of ambient coral reef resource quality values or statements of condition that relate to the desired biological integrity for that class of coral reef ecosystem. When established they can be used to evaluate similar coral reef ecosystems in that region. Implementation of biocriteria requires use of bioassessment protocols and a state or regional biomonitoring database. The National Program Guidance for biocriteria described issues related to development and implementation

(USEPA 1990a). The first biocriteria technical guidance developed was for streams and small rivers (Gibson et al. 1996). It incorporates both biosurvey techniques and biocriteria development methods. This same approach is being followed in similar documents for lakes and reservoirs, rivers, and wetlands, in addition to the latest technical guidance for estuaries and coastal marine waters (Gibson et al. 1997). It is hoped this study will provide a foundation for a similar biocriteria guidance document for coral reef ecosystems.

CHAPTER 2
Does Sufficient Need Exist To Prepare A Guidance Document On Coral Reef Ecosystem Biocriteria

2.1 THE NEED

Sufficient need does exist to prepare a guidance document on coral reef ecosystem biocriteria for the following reasons.

Coral reef ecosystems are sensitive indicators of poor coastal zone management practices because they are the downstream recipients of watershed pollutants. For many coral reef ecosystems, the effective watershed not only includes adjacent terrestrial components but also includes a seaward component via oceanic currents that can carry pollutants from distant sources. One could argue the watershed for the Florida reef tract not only includes the runoff from the State of Florida but also includes pollution, sediments and nutrients from rivers and other sources located in Gulf of Mexico states, the Caribbean and South America. The use of coral reefs for commercial and recreational activities also makes overexploitation (i.e., overfishing) and coastal zone carrying capacity problems (i.e., overdiving - physical reef damage) evident to frequent users.

Of the approximate 600,000+ km2 of coral reefs world-wide, it is estimated that about 10 percent have already been degraded beyond recovery and another 30 percent are likely to decline significantly within the next 20 years (IUCN 1993).

All the coral reef ecosystems under U.S. jurisdiction near large human population centers are experiencing local anthropogenic related stress (e.g., overfishing, eutrophication, sedimentation, physical damage (Jameson *et al.* 1995a, Jameson 1995b).

Almost all of the reefs off **Florida** are at risk from a range of factors, including runoff of fertilizers and pollutants from farms and coastal development (Burke et al. 1998). South Florida and Florida Keys seagrass beds, including those of Florida Bay and along the reef tract, cover an estimated 5, 500 km2. In 1987 a massive mortality of seagrasses occurred resulting in the loss of over 40 km2 of seagrass beds. Seagrass mortality has persisted at a lower pace since 1990. A combination of ambient conditions that inhibited the sustainability of the seagrass community and the susceptibility to increased organic loadings from domestic wastes in artificial waterways and dead-end canals within the Keys are possible explanations. Little is known concerning the recent mortality of mangroves but there appears to be a rough spatial correlation with adjacent areas of high salinity in Florida Bay. Evidence is growing that freshwater management practices as far north as Lake Okechobee are having serious effects on coral reef health and coral recruitment (Porter 1995). Unfavorably warm conditions during long-lasting summer doldrums have been linked to coral bleaching. Add to this equation the four-fold increase in local human population since 1930, impacts from land use (sedimentation), water pollution (point, nonpoint and external sources - eutrophication, leaching of land-based septic systems), boating, recreational and commercial fishing, and the activities of over 3 million tourists a year and one is faced with a coral reef ecosystem struggling for survival. The impacts of fishing are particularly significant because recreational fishing is the area's primary tourist-related boating activity, and commercial fishing is the fourth largest industry in the region. There are well-documented reports of local declines in coral populations from monitoring, but there is uncertainty about the areal extent of these changes (USDOC 1994).

Due to rapid development over the last 50 years, two-thirds of **Caribbean** reefs are in jeopardy and most are threatened by pollution effluents from adjacent densely populated islands (Burke et al. 1998). Coastal development has had significant environmental impact, through increased turbidity, on the majority of the Caribbean islands. Tourist-related threats include anchoring, littering, trampling, diver damage and over-collection of coral. Both commercial and recreational fishing pressure, as well as destructive fishing techniques, such as fish traps, poison and blast fishing, and spearfishing, have led to significant declines in fish, lobster, and coral populations. Virtually all of the reefs off **Puerto Rico** are threatened and deforestation has led to erosion and increased soil run-off, causing significant siltation of reefs (Burke et al. 1998). This problem is often aggravated by the input of fertilizers, pesticides, and other agricultural pollutants. Mangrove depletion has been prominent in the majority of the Caribbean islands including Puerto Rico, and the **U.S. Virgin Islands**. In the U.S. Virgin Islands most of the reefs are at high risk (Burke et al. 1998). In the Caribbean, less than 10% of total domestic waste receives treatment before disposal and much reaches coastal waters, causing eutrophication and accelerated algal growth. Sewage pollution has been reported from Puerto Rico and the U.S. Virgin Islands. Oil terminals/refineries (and associated construction activities), tanker traffic, and offshore oil reserves adjacent to the reefs are also of concern in the Caribbean and the threat of related pollution is serious in Puerto Rico and U.S. Virgin Islands. Caribbean coral reef ecosystems also have been afflicted with natural damage due to hurricanes and prolonged algal blooms following the Caribbean-wide mass-mortalities of Diadema antillarum in 1983. The lack of herbivory, due to the loss of Diadema and chronic overfishing, has allowed algae to replace coral in many areas, particularly after the coral has been reduced during recurrent hurricanes (IUCN/UNEP 1988).

Almost half of **Hawaii's** reefs are vulnerable (Burke et al. 1998). All coral reef habitats in the main Hawaiian Islands are overfished in various degrees. Each main island in the chain is characterized by specific but localized anthropogenic induced problems that are geographically unique and most are found where water circulation is restricted. Sedimentation and eutrophication are generally the most serious problems (Grigg 1997).

U.S. coral reef ecosystems in the **Central Pacific** are also feeling anthropogenic impacts. Military testing and training is active on Johnston Atoll and there are severe residual effects from military construction activities at Palmyra and Johnston Atolls and Wake Island. The remote U.S. islands of Palmyra and Kingman are likely subjected to illegal poaching (Maragos 1997). Dahl (1981) and Dahl and Lamberts (1977) found deteriorating conditions in Samoa.

Fish populations have been seriously affected by human fishing pressure in the **Southern Marianas** and exhibit substantial decreases in catch per unit effort, decreases in abundances of fishes, and major shifts in relative abundance with the decrease in species targeted by fishermen. The most insidious effects are decreases in reproductive potential (as much as 95%) for populations of fishes which are still common but which show major decreases in size distribution. Data from permanent transects show that coral communities have withstood effects of increased tourism since the 1970's, but increased rates of sedimentation and overfishing of herbivores may have reduced the rates of coral replenishment (Birkeland 1997).

2.2 THE SOCIO-ECONOMIC VALUE OF U. S. CORAL REEF ECOSYSTEMS

Coral reef ecosystems are valuable for many reasons. They provide thousands of U.S. residents with food, tourism revenue, coastal protection and new medications for increasingly drug-resistant diseases - despite being among the least monitored and protected natural habitats in the world.

In 1990 the coral reefs of Florida alone have been estimated to generate about $1.6 billion from recreation uses (USDOC 1994).

For many Caribbean countries, tourism is now the key economic sector, often providing over 50% of GNP, and growing very fast. In 1990, Caribbean tourism earned $8.9 billion and employed over 350,000 people (Jameson et al. 1995a).

In Hawaii, coral reefs are central to a $700 million and growing marine recreation industry. Reef fish, lobsters, and bottom fish generate about $20 million in landings annually and are an important source of food for local and restaurant consumption (Grigg 1997). Diving brings $148.6 million annually to Guam (Birkeland 1997).

As much as 90% of the animal protein consumed on many Pacific Islands comes from marine sources (IUCN 1993).

2.3 EPA LEGISLATIVE MANDATES

The U.S. Environmental Protection Agency has several legislative requirements related to coral reef ecosystem protection. These are related to the Clean Water Act and the Florida Keys National Marine Sanctuary (FKNMS) and Protection Act.

2.3.1 Clean Water Act

The Clean Water Act, Section 101, requires federal and state governments to "restore and maintain the chemical, physical, and biological integrity of the nation's waters." Thus, the Act mandates the restoration and maintenance of biological integrity in the Nation's waters. The combination of performing biological assessments and comparing the results with established biological criteria is an efficient approach for evaluating the biological integrity of coral reef ecosystems. Other pertinent sections of the Clean Water Act are Sections 305(b), 301 (h), and 403(c).

2.3.2 305(b) Reporting

States and the USEPA report on the status and progress of water pollution control efforts in 305(b) reports submitted every five years. Inclusion of biological assessment results in these reports will improve the public understanding of the biological health and integrity of water bodies. Many of the better known and widely reported recoveries from pollution have involved the renewal or reappearance of valued species to systems from which they had nearly disappeared, or systems cleaned to the point that people can harvest and consume the fish and shellfish. Examples of such recoveries are the restoration of the lower Potomac River and shellfish beds in Maine. Incorporation of biological integrity in 305(b) reports will ensure the inclusion of a bioassessment endpoint, and will make the reports more accessible and meaningful to many segments of the public.

2.3.3 301(h) And 403(c) Programs

Two other programs within USEPA that specifically rely on biological monitoring data in coastal marine areas are the 301(h) waiver program and the 403(c) ocean discharger program. The 301(h) program allows marine dischargers who meet specific criteria set forth by USEPA to defer secondary treatment if they can show that their discharge does not produce adverse effects on resident biological communities. As part of the modified NPDES permit received through this waiver program, the dischargers are required to conduct extensive biological monitoring programs designed to detect detrimental effects to those biological communities.

The 403(c) ocean discharge program (also part of the Clean Water Act) requires that all dischargers to marine waters provide an assessment of discharge impact on the biological community in the area of the discharge and on the surrounding biological communities. This program requires extensive biological monitoring for some dischargers. Community bioassessment methods are valuable in this program for trend assessment and, in some cases, refinement into more rigorous and definitive assessments.

2.3.4 Clean Water Action Plan

This plan was developed by the U.S. Department of Agriculture and the U.S. Environmental Protection Agency, in collaboration with other affected Federal agencies (USEPA 1998). This plan considers the restoration and protection of water quality through three major goals: (1) enhanced protection from public health threats posed by water pollution; (2) more effective control of polluted runoff; and (3) promotion of water quality protection on a watershed basis. This plan will build upon existing frameworks such as the Clean Water Act sections, 305(b), 303(d), and 319. The watershed approach to management allows for a more efficient implementation of point and non-point source controls and are intended to enhance the protection of sensitive natural areas such as coastal ecosystems.

2.3.5 Florida Keys National Marine Sanctuary Requirements

Recognizing the critical role of water quality in maintaining sanctuary resources, Congress directed the U.S. Environmental Protection Agency and the State of Florida, represented by the Florida Department of Environmental Protection, to develop a Water Quality Protection Program for the sanctuary. This is the first such program ever developed for a marine sanctuary.

The purpose of the Water Quality Protection program is to recommend priority corrective actions and compliance schedules addressing point and nonpoint sources of pollution to restore and maintain the chemical, physical, and biological integrity of the sanctuary. This includes restoration and maintenance of a balanced, indigenous population of corals, shellfish, fish and wildlife, and recreational activities in and on the water.

In addition to corrective actions, the 1990 Florida Keys National Marine Sanctuary and Protection Act (Public Law 101-605) also requires development of a water quality monitoring program and provision of opportunities for public participation in all aspects of developing and implementing the program.

2.4 THE MANAGEMENT NEED

The biocriteria-bioassessment process, as outlined in 1.3, helps coral reef ecosystem managers identify impairment of sites designated by the government for special uses (i.e., national marine sanctuary, harbor, etc.). It expands and improves designated beneficial use classifications and their associated water quality standards. It detects problems other survey methods may miss or underestimate. It is a process which helps the resource manager set program priorities. And it can be used to evaluate management and regulatory efforts.

2.4.1 Identifying Impairment Of Special Designated Use Sites

By comparing monitoring data to established biocriteria, the impairment of designated special use sites - such as national marine sanctuaries with coral reef resources - can be evaluated.

2.4.2 Expansion And Improvement Of Water Quality Standards

When EPA and a State elect to incorporate biological criteria in their designated use water quality standards (i.e., for the Florida Keys National Marine Sanctuary), these criteria serve not only to refine those standards, they become benchmarks for decision making as well as elements for regulatory decisions when the standards are enforced.

2.4.3 Detection Of Problems Other Methods May Miss Or Underestimate

Coral reefs are efficient recyclers. As a result, chemical pollutants (i.e., nitrates and phosphates in a eutrophication situation) are taken up by the system at extremely rapid rates. In many cases, water sampling can not detect a significant change in water quality whereas detrimental changes could be detected using biocriteria that included bioindicator species.

Also, in the process of establishing biocriteria, more data and information is inevitably recorded than was previously available. The review of this new information often reveals problems not evident before or provides expanded insight into existing concerns and issues. With this information, the coral reef ecosystem resource manager is often able to view his responsibilities from a new and expanded perspective.

2.4.4 Helping The Water Resource Manager Set Priorities

In light of the new information described above, the schedule of activities, allocation of funds, and uses of personnel and equipment may be more appropriately prioritized according to the urgency or magnitude of the problems identified. With the expanded available biological information augmenting chemical and physical information, managers can apply a triage approach to water resource projects based on the actual condition of the coral reef affected. This is much like a physician evaluating multiple emergency medical patients. Essentially, areas that are critically impaired, those that are moderately impaired, and those in good condition for which protection rather than remediation is required, can all be identified. Rational decisions can then be made about how to apply limited resources for the best results.

2.4.5 Use Of Bioassessment And Biocriteria To Evaluate The Success Or Failure Of Coral Reef Ecosystem Management Initiatives Or Regulations

A coral reef manager may design a biosurvey to collect data before and after a permit, regulation or other management effort has been implemented, perhaps augmented by spatially distributed nearfield/farfield sampling as well. With this information and the biocriteria decision-making benchmark, it is possible to clearly evaluate the environmental response of the system to the methods applied. This process is particularly appropriate to the National Pollution Discharge Elimination System (NPDES) permit review procedure. It is not necessary or advisable at this time that biocriteria be incorporated in NPDES permits. But biomonitoring above and below a permit site when compared to the established biocriteria will reveal the adequacy of the permit to achieve its intended purpose. If the coral reef biota are unimpaired or recovering, it may be wise to leave the permit, management practice or regulation as is. If the coral reef biota are impaired or declining, the review recommendation may be to change the permit, management technique or regulation accordingly. With NPDES permits, the five year review cycle - especially if permit reviews are on a staggered, rotating basis - allows sufficient time for extensive biological information to be developed so this determination can be made with reasonable confidence.

2.5 PROGRAMMATIC NEEDS

2.5.1 EPA Ecological Risk Assessment Program Benefits

Increased interest in ecological issues such as global warming, habitat loss, acid deposition, reduced biological diversity, and the ecological impacts of pesticides and toxic chemicals prompted EPA to establish the Ecological Risks Assessment Program. EPA's Framework for Ecological Risk Assessment (USEPA 1992) and Guidelines (USEPA 1998) offers starting principles and a simple structure as guidance for current ecological risk assessments and as a foundation for future EPA proposals for risk assessment guidelines. Biocriteria can provide a firm biological foundation for ecological risk assessment.

2.5.2 U.S. National Marine Sanctuary Designation Priorities

Historically, designation of national marine sanctuaries has been to a large degree threat-driven. All sanctuaries to date have been designated because they are in danger of being irrevocably damaged due to human impacts. The need for reference sites as part of a national coral reef ecosystem biocriteria program would clearly establish the necessity for protecting remote and in many cases unthreatened sites as national marine sanctuaries. Identifying reference sites for a coral reef ecosystem biocriteria program will help national marine sanctuary leaders focus on these areas for future sanctuary designations.

2.5.3 U.S. And International Coral Reef Ecosystem Monitoring Programs

A coral reef ecosystem biocriteria program with associated reference sites would provide a focal point and standard framework for monitoring efforts in U.S. National Marine Sanctuaries and for researchers working on U.S. coral reef ecosystems not under the sanctuary umbrella. This biocriteria program framework could also be transferred to other nations with coral reef ecosystem management responsibilities.

In addition, biocriteria, indices and monitoring data would be of great value to the recently established Global Coral Reef Monitoring Network (GCRMN) and could be used as a yardstick for NGO and volunteer monitoring programs, such as Reef Check, to compare their data against.

Using standard biocriteria for evaluating the condition of U.S and other coral reef ecosystems will also provide more realistic and reliable regional and global perspectives on coral reef resource status and trends.

CHAPTER 3
Does Sufficient Information Exist to Draft Biocriteria Guidance

3.1 ROLE OF THE 1997 EPA ESTUARINE & COASTAL MARINE WATERS BIOASSESSMENT & BIOCRITERIA TECHNICAL GUIDANCE

While a separate guidance document will be needed for the U.S. Coral Reef Ecosystem Biocriteria Program, the 1997 USEPA Draft Estuarine & Coastal Marine Waters Bioassessment & Biocriteria Technical Guidance (Gibson et al. 1997) provides a useful framework to design the U.S. Coral Reef Ecosystem Biocriteria Program around.

3.2 DIVERSITY OF BIOINDICATORS

Traditionally, bioindicators have referred to indicators using non-human organisms. However, with the growing realization that man is the root cause of many problems in the coastal zone and in coral reef ecosystems (Jameson et al. 1995a), bioindicators that are more anthropogenic-focused (i.e., FACT, Map-Based and RAMP) are also discussed in this report's consideration of potential indicators for a U.S. Coral Reef Ecosystem Biocriteria Program.

3.3 EXISTING U.S. PROGRAMS RELEVANT TO CORAL REEF ECOSYSTEM BIOASSESSMENT AND BIOCRITERIA DEVELOPMENT

Sustainable monitoring programs are critical for a successful biocriteria program. Unfortunately, the cost of coral reef ecosystem monitoring is expensive and government and private budget support has historically been inconsistent (Jameson et al. 1995a).

There are only 4 examples of long-term (greater than 5 years in duration) coral reef ecosystem monitoring programs in U.S. waters that are still ongoing today (Table 3.1). All of these programs except CARICOMP - Puerto Rico are government funded. The other 5 notable long-term efforts (Table 3.2) have been intermittent in their sampling timing and for the most part are privately funded (Ginsburg 1994).

Many short-term or project-specific monitoring efforts have been conducted by universities, students, and marine laboratories, but repeating these is, in many cases, dependent on the cooperation of the personnel who conducted the original work. Data from these short-term monitoring efforts (less than 5 years in duration) could be useful building blocks for a U.S. biocriteria program and the potential of each of these efforts should be evaluated.

Table 3.1: Summary of past and existing long-term (greater than 5 years) monitoring programs relevant to coral reef ecosystems under U. S. jurisdiction.

Program	Location	Period	Status	Parameters	Contact
Flower Gardens National Marine Sanctuary Monitoring Program	Gulf Of Mexico	1972 -present	**Ongoing**	Photo techniques and direct measurements of coral cover, population levels, diversity, evenness, accretionary - encrusting growth	Steve Gittings 301-713-3145
Virgin Islands National Park	U.S. Virgin Islands - St. John	1989 -present	**Ongoing**	Coral & macroalgae cover, coral physical damage, disease & fish catch	Caroline Rogers 809-693-8950
CARICOMP	Puerto Rico	1993 -present	**Ongoing**	CARICOMP Level 1	Jorge Garcia 809-899-2048
NOAA Mussel Watch Program	Florida Keys (6 sites), Hawaii (4 sites)	1986 -present	**Ongoing**	Trace metals and organic compounds	Gunnar Lauenstein 301-713-3028 X152
NOAA Status & Trends - Benthic Surveillance	Florida Keys & vicinity - some cruises with EPA/EMAP	1984-1994	Stopped	Sediment samples, fish chemistry, fish biology	Bernie Gottholm 301-713-3034 X168
Dry Tortugas National Park Coral Reef Monitoring	Florida - Dry Tortugas (3 sites)	1989 - 1995	Stopped	Quadrate sampling of stony & soft coral spp. abundance, diversity & evenness	Walter Jaap 813-896-8626

Table 3.2: Summary of notable existing intermittent long-term (greater than 5 years) monitoring programs on coral reef ecosystems under U. S. jurisdiction.

Program	Location	Period	Status	Parameters	Contact
Harbor Branch - Carysfort Reef	Florida	1974 - 1982	Intermittent	Coral cover, diversity, recruitment, & mortality	John Halas 305-451-7717
The History of *A. palmata*	Florida - Dry Tortugas	1881 - 1993	Intermittent	Distribution & abundance	Walter Jaap 813-896-8626
University of Georgia - Institute of Ecology	Florida - Looe Key (2 sites), Key Largo (2 sites), Biscayne National Park (2 sites)	1984 - 1991	Intermittent	Photo stations monitoring species number, % cover, & species diversity for scleractinia & hydrozoan corals	James Porter 706-542-3410
Kaneohe Bay	Hawaii - Kaneohe Bay	1970 - 1990	Intermittent	Changes in coral & algal cover, changes in coral spp. diversity	Cynthia Hunter 808-956-3946
University of Guam technical reports, theses, publications	Marianas Islands - various locations	Starting in late 1960's	Intermittent	Coral cover & recruitment, sedimentation, fish catch	Charles Birkeland 671-735-2184

3.3.1 1996 EPA Water Quality Protection Program For The Florida Keys National Marine Sanctuary

The 1996 EPA Water Quality Protection Program for the FKNMS (FKNMS-WQPP) is a new initiative (USEPA 1996) that could provide the basis for a biocriteria program in the Florida Keys, if funding remains sustainable. Table 3.3 summarizes the different facets of this program.

Table 3.3: Florida Keys National Marine Sanctuary Water Quality Protection Program.

Program	Location	Period	Status	Parameters	Contact
Coral reef & hard bottom monitoring	Florida Keys National Marine Sanctuary (40 sites)	1996 - present	**Ongoing**	Video sampling to determine net reef changes in% cover, stony coral spp richness, net changes in reef community parameters, changes in reefs compared to entire ecosys, & changes linked to specific regions of land	Florida Marine Research Institute - Jennifer Wheaton 813-896-8626
Water quality monitoring	Florida Keys National Marine Sanctuary (150 sites)	1996 - present (Quarterly monitoring)	**Ongoing**	Dissolved nutrients, chl a, APA, ppt, temp, DO, NTU and k	Florida Intl. University - Ronald Jones 305-348-3095
Seagrass monitoring	Florida Keys National Marine Sanctuary (300+ sites)	1996 - present	**Ongoing**	Distribution/ abundance, demographics, productivity of dominant species, nutrient availability	Florida Intl. University -Jim Fourqurean 305-348-4084
Data management	Florida Keys National Marine Sanctuary	1996 - present	**Ongoing**	Design data management plan & system and implement system	Florida Marine Institute - Chris Friel 813-896-8626

3.3.2 1996 EPA Water Quality Special Studies Program For The Florida Keys National Marine Sanctuary

The objective of the Special Studies Program is to identify and understand cause and effect relationships among pollutants, transport pathways, and the biological communities of the sanctuary (USEPA 1996). The results of the studies outlined in Table 3.4 will be important in developing biological criteria for coral reef ecosystems in the FKNMS.

Table 3.4: Florida Keys National Marine Sanctuary Water Quality Protection Program Special Studies.

Program	Location	Period	Status	Parameters	Contact
Semi-synoptic sampling of phyto-plankton to locate nutrient inputs	FKNMS	1995 -present	**Ongoing**	Phytoplankton abundance (chlorophyll) after large rains	University of Miami - Larry Brand 305-361-4600
Use of natural & artificial tracers to detect subsurface flow of contaminated ground-water	FKNMS	1995 -present	**Ongoing**	Measures Rn, CH4, N to locate ground-water seeps. Injects SF6 and I into cess-pools, septic tanks, disposal wells to assess linkage to sewage disposal and measure flow rate	Florida State University - Jeffrey Chanton 805-644-7493
Symbiotic algae as indicators of nutrient exposure	FKNMS	1995 -present	**Ongoing**	Ammonium enhancement of dark carbon fixation by algae, methyla-mine uptake by algae, free am-ino acid content of algae & corals, CNP ratio of algae & coral tissue, coral growth rates	Harbor Branch Oceanographic Institution, Clayton Cook 407-465-2400
Algal tissue nutrients as indicators of nutrient enrichment	FKNMS	1995 -present	**Ongoing**	Determine temporal and spatial variation relative to sources of wastewater pollutants of tissue CNP of macro-algae & seagrass epiphytes, identify hotspots, select indicator spp.	Harbor Branch Oceanographic Institution, Dennis Hanisak 407-465-2400
Wastewater nutrients in ground waters: contrasting behaviors of phosphorous & nitrogen	FKNMS	1995 -present	**Ongoing**	Installs monitoring wells of varying depths surrounding injection wells to assess potential for transport of anthropogenic nutrients from sites of injection to zones of ecological sensitivity	Pennsylvania State University, Lee Kump 814-865-4700
High frequency monitoring of wastewater nutrient discharges and their ecological effects	FKNMS	1995 -present	**Ongoing**	Use biomass, tissue CNP ratios, alkaline phosphatase activity & 14N/15N ratios to monitor effects of wastewater nutrient inputs	Harbor Branch Oceanographic Institution, Brian Lapointe 407-465-2400
Groundwater seepage demonstration project	FKNMS	1995 -present	**Ongoing**	Construct clean enclosure around groundwater seep with check valve and evaluate effect of enclosure against control site (no seep)	U.S. Geological Survey, Eugene Shinn 813-893-3100
Hawk Channel transport study	FKNMS	1995 -present	**Ongoing**	Quantify volume transport over seasonal and annual time scales through selected passes and document storms, determine flow patterns in Hawk Channel, identify mechanisms that exchange water between Hawk Channel and the Florida Straits, determine wind driven exchanges, determine advection and diffusion processes in transporting Florida Bay water across Hawk Channel	Harbor Branch Oceanographic Institution, Ned Smith 407-465-2400

3.3.3 Other New Monitoring Initiatives In The Florida Keys National Marine Sanctuary

Table 3.5 lists several new monitoring initiatives that could provide valuable long-term baseline data to the U.S. Coral Reef Ecosystem Biocriteria Program.

Table 3.5: Other new monitoring initiatives in the Florida Keys National Marine Sanctuary.

Program	Location	Period	Status	Parameters	Contact
CARICOMP - Florida Keys	To be determined	Starts in 1998	**Ongoing**	CARICOMP Level 1	Florida Institute of Oceanography John Ogden 813-553-1100
FIO Benthic Monitoring	No-take zones in the FKNMS	5 year contract with NOAA	**Ongoing**	TV techniques and coral recruitment studies using precision photography	Florida Institute of Oceanography John Ogden 813-553-1100
NOAA/EPA Dry Tortugas Baseline Data Program	Dry Tortugas National Park	1997 - 2002	**Ongoing**	Biological inventory & habitat mapping for ecological reserve characterization	NOAA, Michael Crosby 202-482-2977
EPA Disease Studies	Dry Tortugas to Key West	1996 - 2001	**Ongoing**	Distribution & abundance of disease, monitoring of water quality, analysis of infected coral samples	EPA Ocean & Coastal Protection Division - Ken Potts 202-260-7893

3.3.4 Florida Assessment Of Coastal Trends (FACT)

FACT is the nation's first coastal environmental indicator system. First initiated in 1995 by the Florida Coastal Management Program via contract to the Florida Center for Public Management, FACT 1997 (Bergquist *et al.* 1997) updates data in the indicators, deletes indicators with poor or nonexistent data sources, adds new indicators to improve the system and reformats the individual indicator sheets to improve their graphic effect.

The coral reef ecosystem component of FACT 1997 includes the EPA coral reef/hard bottom monitoring program (USEPA 1996) coordinated by Jennifer Wheaton of the Florida Marine Research Institute (Table 3.3).

3.3.5 State Of Florida Environmental Indicator Technical Assistance Series

The 1996 State of Florida Environmental Indicator Technical Assistance Series is terrestrial oriented. However, some indicators (i.e., water quality, air pollutants, climate change, ozone depletion, atmospheric deposition, pesticides, accidental releases, ecosystems land use/land cover, use and management of natural resources) in this series warrant further investigation as components of a Florida Keys focused coral reef ecosystem biocriteria program.

Likewise, certain aspects of the U.S. Coral Reef Ecosystem Biocriteria Program may also be beneficial to this indicator program.

3.3.6 International Umbrella Programs

Two international umbrella monitoring programs that are relevant to a U.S. Coral Reef Ecosystem Biocriteria Program include:

- The Global Coral Reef Monitoring Network (GCRMN). The GCRMN database would benefit from the U.S. Coral Reef Ecosystem Biocriteria Program bioassessment data and would be very interested in any indices developed as part of the biocriteria program.

- The Caribbean Coastal Marine Productivity Program (CARICOMP). CARICOMP Puerto Rico could provide data to the U.S. Coral Reef Ecosystem Biocriteria Program and would also benefit from new indices developed as part of the biocriteria program.

3.4 REVIEW OF POTENTIAL CORAL REEF ECOSYSTEM BIOINDICATORS FOR BIOASSESSMENT AND BIOCRITERIA DEVELOPMENT

Indicator organisms have a long history of use for detecting qualities about an environment that are otherwise difficult to perceive, from the well-known "canary in the coal mine" to the highly successful "Musselwatch" program in North American bays (Soule 1988). Freshwater and marine organisms have been used extensively as bioindicators since the 1970's (Phillips 1980).

The use of bioindicators has been justified in marine pollution monitoring programs for at least three reasons (Maher and Norris 1990).

- First, they assess only those pollutants which are bioavailable, ostensibly those which are most important.

- Secondly, they can reveal biological effects at contaminant levels below current chemical analytical detection limits (either due to chronic, low level pollution or short-term pulses).

- Finally, bioindicators can help assess synergistic or additive antagonistic relationships among pollutants, an important consideration with the typical combination of pollution impacts impinging on most reefs in the developing world (Ginsburg 1994).

Bioindicators can be classified into several main groups, including in-situ pollution indicators (Kovacs 1992, Root 1990), transplanted or naturally-occurring bioaccumulating indicators (de Kock and Kramer 1994), indicators used in laboratory toxicity-testing (Cairns and Pratt 1989, Kimball and Levin 1985), and most recently, biodiversity bioindicators (Noss 1990, Pearson 1994). Of these major groups, bioindicators have been used most effectively and extensively for in-situ freshwater and temperate marine pollution monitoring (e.g., Lenat 1980, Lenat et al. 1988, Soule and Kleppel 1988, Faith 1990 and Rosenberg and Resh 1993). Though coral reef bioindicator systems are not as well developed as those for freshwater and temperate marine habitats, the majority of those proposed are also in-situ pollution/stress indicators. As such, this review shall focus primarily upon this type of bioassessment.

Continuing development of freshwater and marine bioassessment protocols over the past three decades has led to the recognition of a number of important criteria for selection of indicator organisms (e.g., Phillips 1980, Soule 1988, Wenner 1988, Kovacs 1992, Jones and Kaly 1996). Most workers agree that the indicator organism(s) should be abundant throughout the monitoring area and easy to sample in an objective, quantitative manner. Indicators should not be subject to direct human exploitation, which would obviously confound any trends in monitoring their abundance or other population parameters. Additionally, it is highly advantageous if the organism(s) have a stable taxonomy which is easily taught to non-specialists; Cranston (1990) makes a strong case for the importance of identification to the species level in all bioassessment programs (though see Warwick (1988) for a different view).

Perhaps most importantly, bioindicators should provide an early warning of sublethal stresses to the primary habitat-structuring organisms (scleractinian corals, in the case of coral reefs), in order that management actions can be taken before the reefs begin serious decline. Brown (1988) and Jones and Kaly (1996) have further argued that coral reef bioassessment should focus on monitoring hard corals directly, as these are the most "important" organisms on the reef. While this view certainly has merit, it seems reasonable that indicator species which respond to the same stressors as the corals, but in a more sensitive manner, should also provide a useful early warning of deteriorating conditions on a reef.

A related criteria holds that the organism should reveal gradations in response relative to the level of stress (e.g., level of pollution). Similarly, Noss (1990) suggests that indicators should be capable of providing a continuous assessment of stress over a wide range of stress (i.e., euryoecious species). This criterion has been disputed in the literature by those who suggest that sensitive species with narrow environmental tolerances (stenoecious species) are more suitable as bioindicators (e.g., Lang et al. 1989). Certainly, a case can be made in favor of either viewpoint, depending on the objectives of the monitoring program. Nonetheless, as a general rule, the absence of a sensitive organism in a monitoring situation is much less informative than reduced abundance or other graded responses (Podani 1992). At best, the simple presence or absence of a sensitive species provides information on whether certain threshold conditions have been surpassed; whereas a graded response in abundance or some other organismal parameter can provide more detailed information on the level of ecosystem stress (e.g., extent of eutrophication).

Similarly, Erdmann and Caldwell (1997) suggest that a useful bioindicator should show a response which is indicative of a relatively small number of anthropogenic stressors (i.e., response specificity). Brown (1988) provides a contrary opinion, suggesting that a generalized response to a wide range of environmental stressors (such as zooxanthellae loss in corals) is preferable for bioassays. However, such a generalized response would seem to contradict a primary objective of using bioindicators (viz. to provide an early warning of sublethal stresses in order that management actions can be taken to ameliorate this stress). As Wells (1995) points out, "if the cause of a change on a reef is not known, finding the correct management solution is difficult." With this in mind, response specificity would seem an important criteria in selecting coral reef bioindicators.

Jones and Kaly (1996) discuss three further bioindicator criteria which have been vigorously debated in the literature; these involve the characteristics of mobility and longevity of the indicators, as well as the cosmopolitan nature of the indicator. A number of workers (e.g., Bilyard 1987, Alcolado et al. 1994) have suggested that sessile or sedentary organisms are an obvious first choice for biomonitoring, as these organisms are continuously exposed to local environmental conditions. Reese and coworkers (Reese 1981, Hourigan et al. 1988) have argued that to the contrary, mobile species are preferable in biomonitoring, as they can simply move when environmental conditions begin to deteriorate - thus providing an early warning of stress. Though the majority of biomonitoring programs in practice today seem to focus on benthic, sessile or sedentary organisms (see Spies 1984 for further theoretical backing), both viewpoints are easily supported, and the characteristic of mobility appears to have little value as an absolute standard for choosing a bioindicator. Similarly, the value of cosmopolitan indicators, though often championed by proponents of standardized, widespread bioassays such as the Musselwatch program (Goldberg et al. 1978), is debatable. As Jones and Kaly (1996) point out, organisms with extremely limited ranges are ostensibly most at risk of extinction, and therefore likely candidates for monitoring.

A final organismal characteristic with strong proponents in favor of either extreme is organismal longevity. Hourigan et al. (1988) and Crosby and Reese (1996) suggest that long-lived organisms which tolerate low-level, chronic stresses for long periods of time will be able to provide an integrated signal of this stress which species with short generation times might not. They also point out that it is often easier to detect changes in populations of longer-lived species. At the other extreme, species with short generation times often respond very quickly to environmental changes (Jones and Kaly 1996), which suggests that they may be a more sensitive choice of bioindicator. Furthermore, as Brown (1988) points out, it is generally the juveniles and new recruits of a particular organism which are the most sensitive to environmental stress, especially water quality deterioration. Numerous studies support the concept that larval settlement and recruitment are often the ecological processes most affected by marine pollution, rendering the consideration of species longevity irrelevant (Gajbhiye et al. 1987, Hernnkind et al. 1988, Jackson et al. 1989, Erdmann and Caldwell 1997). Clearly, all three of the aforementioned criteria are highly debateable and have limited value as absolute standards for selection of bioindicators.

Rather, the application of these indicators will depend on the particular monitoring questions being asked.

The universal importance of considering recruitment issues in designing marine bioassessment programs is rarely debated, however. For bioassays which will measure species abundance, for example, it is highly preferable to choose organisms which demonstrate recruitment which is independent of the organism's population size at any given site, in order to avoid autocorrelation in abundance measures over time (Garrity and Levings 1990). Likewise, it may be preferable to select organisms which are not normally subject to natural, drastic fluctuations in recruitment, as this would also confound interpretations of species abundance measures. This problem is somewhat ameliorated by selecting species which demonstrate multiple recruitment periods per year. Not only would this prevent a single, naturally poor recruitment period from dominating abundance measures for long periods of monitoring, but it would also provide multiple opportunities to detect negative impacts of low-level, intermittent stress on new recruits. Such criteria are obviously more germaine to bioassessment programs which involve frequent sampling during the course of a year.

Despite the above precautions, however, a potential problem with using indicator species to monitor coral reefs is that natural fluctuations are inherent to such complex systems, and hence monitoring abundance of a particular taxa may be inconclusive or misleading (Spellerberg 1991). This problem is partly alleviated by monitoring multi-species assemblages, as similar population responses in a number of different taxa should help reduce "noise" associated with natural fluctuations in abundance of a given species (Soule 1988). However, Brown (1988) and Wenner (1988) further suggest that simply monitoring abundance and diversity measures can be insensitive. Osenberg et al. (1994) point out that monitoring individual-based parameters such as growth rate and fecundity measures can reveal sublethal differences between populations that abundance and diversity measures alone might miss. Biomonitoring programs which include such measures should obviously choose indicator organisms which have readily ascertainable (and measurable) growth, reproduction, and recruitment.

Finally, Risk et al. (1995) and Erdmann and Caldwell (1997) discuss several further criteria which are specific to bioassessment programs designed for use in local, community-based coral reef management projects (such as those in many developing countries). Those authors suggest that bioassays for these programs should be inexpensive, require a low-capital equipment investment (i.e., the use of SCUBA may be inappropriate), and should be easily taught to local participants with at most a high-school science background.

Obviously, the above discussion of bioindicator selection is provided as a general guide; there is no one "perfect" bioindicator (Cairns 1986), and not every characteristic discussed is applicable to every proposed bioassessment. Jones and Kaly (1996) warn against a "shopping list" approach to selecting bioindicator organisms. Rather, selection of the most appropriate bioindicators for a particular biomonitoring program depends upon the monitoring question(s) being investigated, as well as the specific monitoring situation expected (including regional, financial, level-of-expertise, and time considerations). As the science of coral reef management develops, there is an increasing awareness that management objectives and methods will vary significantly between regions and countries, contingent upon the status and use of reefs in those areas (Done 1995, Wells 1995). Clearly, bioassessment protocols should reflect this diversity of management objectives, and need to be specifically tailored to meet each monitoring program's needs and capabilities.

The bioindicators discussed below are summarized in table format in Appendices 1 - 5, with additional notes on biogeographic location and season, following the categories used in: Draft Estuarine & Coastal Marine Waters Bioassessment & Biocriteria Technical Guidance (Gibson *et al.* 1997).

3.4.1 Scleractinian Coral Bioindicators

Coral reef monitoring programs have become ubiquitous over the course of the past two decades (Risk 1992, Eakin et al. 1997), ranging from monitoring by individual research scientists to that conducted by large institutions like the Australian Institute of Marine Science or the CARICOMP (Caribbean Coastal Marine Productivity) network. The scope of reef monitoring has recently expanded even further with the introduction of monitoring programs specifically designed for volunteer sport divers, such as the ReefBase Aquanaut and Reef Check programs (McManus *et al.* 1997, Hodgson 1997).

Percentage hard coral cover, diversity indices, and vitality indices

To date, the majority of coral reef monitoring programs have focused on two primary parameters:

1. Percentage of live hard coral cover and;

2. Various indices of the diversity of benthic cover, either at the species or life-form level (Dodge et al. 1982, DeVantier 1986, Gomez and Yap 1988, Aronson et al. 1994, English et al. 1994).

Many workers have discussed the dangers of relying too heavily on these two state variables (e.g., Dustan and Hallas 1987, McLanahan 1997), and some have even questioned their significance. For example, Brown (1988) describes several studies which measured no effect of severe environmental perturbations on coral community diversity indices (though at least one comprehensive study, that of Tomascik and Sander 1987a, did demonstrate a sensitive response of species diversity to eutrophication stress).

Research recommendation: In general, these two parameters are now considered to be important to measure, but insufficient as the sole data used in reef assessment (McLanahan 1997). The realization that 100% live hard coral cover is not a standard to which most coral reefs can compare, even in a pristine state, has led a number of workers to suggest the use of coral "vitality" or "mortality" indices which take into account ratios of live and dead coral cover in an estimation of reef "health" (Grigg and Dollar 1990, Dustan 1994, Gomez et al. 1994, Ginsburg et al. 1996, Steneck *et al.* 1997). Similarly, Aronson et al. (1994) suggest the measurement of reef topographic complexity as a more relevant indicator of reef health than simple percentage live cover. Despite the potential improvements of these methods over measurement of percentage cover and diversity only, and their utility in providing an assessment of reef "health", neither provide an early warning function of deteriorating environmental conditions. Standardized monitoring procedures quantifying coral abundance and diversity are snapshots in time, and are non-predictive. In many cases, impact studies (e.g. sewer outfalls) have been started years after the insult began. In such a case, we must assume that sensitive species have already been eliminated, and that we have reached a stable state. By carefully choosing sensitive scleractinian coral indicator species and transplanting them back to affected areas (over a gradient) we can choose several sub-lethal indicators (possibly growth rate, fecundity, etc) and determine at what distance these are no longer affected. We can then determine if reaching that level of water/substratum quality is cost effective or possible considering the improved conditions for reef recovery.

Brown (1988) reviews a number of additional coral-focused parameters which may provide an indication of sublethal environmental stress and therefore be of particular use in pollution assessment studies. These include:

- measurement of coral growth (skeletal extension) rates;

- calcification and productivity profiles;
- coral fecundity and recruitment;
- monitoring for zooxanthellae loss, coral diseases and cyanobacterial blooms; and
- measurement of the bioaccumulation function of coral skeletons.

Each of these is briefly reviewed below in the context of the bioindicator criteria presented above.

Growth rate

A number of studies have suggested that coral growth rate is one of the most relevant individual-based parameters for measuring declining environmental quality on reefs (reviewed in Brown and Howard 1985). Despite this assertion, the literature provides conflicting evidence of the effects of stress on coral skeletal extension rates. For example, though a number of workers (e.g., Hudson 1981, Cortes and Risk 1985, Rogers 1990) have suggested that massive corals demonstrate a decrease in growth rate under environmental stress such as increased siltation, Brown et al. (1990) found no apparent effect of increased sedimentation on growth rates of Porites on a reef in Thailand which had experienced significant coral mortality due to dredging. Still others (Tomascik and Sander 1985, Risk et al. 1995) report that corals from eutrophied and sedimented sites often demonstrate an initial increase in growth rate due to increased nutrient availability and the use of particulate matter as a food source (though corals on the most eutrophied sites in these studies did show a reduction in growth rates). Edinger (1991) has termed this the "Janus effect", whereby nutrient enhancement can increase coral growth rates up to a certain critical level, after which eutrophication becomes deleterious and growth rates decline.

Research recommendation: Obviously, this phenomena is in need of further research before coral growth rates can be interpreted reliably and their measurement properly calibrated for use in water quality assessment.

Productivity and calcification profiles

Brown (1988) also suggests using productivity and calcification profiles as a means of classifying the status of coral reefs. This bioassay is based upon the concept that healthy reefs operate within narrowly-defined metabolic limits, such that a profile of a reef's performance with respect to these limits should provide an assessment of its current status (Barnes 1983). Theory and data show it is possible to measure productivity and calcification from changes in the oxygen concentration and pH of sea water flowing across a reef flat. When more is known about the variations in the respiratory and metabolic quotients of coral reef benthic communities, it should be possible to characterize the metabolic performance of large areas of reef flat by means of a few transects in the day and at night (Barnes 1983).

Chalker *et al.* (1985) developed a respirometer that can be deployed in situ on coral reefs to a depth of 50 meters for the measurement of primary productivity and calcification by corals, calcareous algae and the communities living on dead scleractinian skeletons using the technique developed by Barnes (1983).

McLanahan (1997) further advocates that the calcium carbonate balance (ratio of carbonate accretion to carbonate erosion) is the "universal currency of reef health and value".

Research recommendation: Though the techniques for measuring these parameters have been developed (e.g., Barnes 1983, Chalker *et al.* 1985), further research focused on applying these techniques to water quality assessment and reef monitoring are clearly needed.

Coral fecundity and recruitment

Two further individual-based coral parameters which Brown (1988) proposes as potentially useful indicators of sublethal stress on coral reefs are coral fecundity and recruitment. Tomascik and Sander (1987b) suggest that coral fecundity is decreased on reefs subject to increased eutrophication, while a number of studies (reviewed in Pearson 1981 and Brown 1988) have detected reduced coral recruitment and even recruitment failure due to a variety of environmental perturbations.

Additionally, ongoing research on pollutant effects on coral fecundity and recruitment (primarily out of the University of Guam) is focused on developing practical and effective methods for assessing coral reef condition and developing predictive tools to be applied to coral reef monitoring and management (Richmond 1993, 1994a, 1994b, 1995, 1996; Peters *et al.* 1997).

Presently accepted protocols, including the use of LC-50's on adult corals or coral reef proxies (e.g. Tilapia) are often inappropriate as well as inadequate for understanding the effects of pollutants on coral reefs. Work on cyanide exposure found some effects were not apparent until two weeks after exposure. In larval recruitment bioassays, larvae exposed to the golf course pesticide Chlorpyrifos had high survivorship, but significantly reduced abilities for recruitment. In a coral reef setting, lack of recruitment is equivalent to direct mortality (Richmond personal communication).

Different life-history stages of corals exhibit differential sensitivities to pollutants. Five chemically-mediated steps have been identified that affect the success of coral reproduction and recruitment:

1) reproductive synchronization among conspecific corals;
2) egg-sperm interactions;
3) embryological development;
4) larval settlement and metamorphic induction; and
5) acquisition of zooxanthellae (for most spawning species).

While adult corals may survive elevated levels of certain pollutants (e.g., organophosphate pesticides), the above five links may be affected by pollutants at extremely low levels. Also, different substances will differentially affect different stages in the reproduction/recruitment cycle: hydrophilic substances will have a greater effect on reproductive synchrony, egg-sperm interactions and embryological development, while hydrophobic/lipophilic substances will affect settlement and metamorphic induction (Richmond 1996).

Research recommendation: Again, this area of research seems particularly promising, and is just starting to be applied in a systematic, calibrated fashion to water quality biomonitoring efforts on reefs. Research is needed to determine the effects of selected pesticides, PAH's and other potential pollutants on corals and coral reefs through the use of fertilization and recruitment bioassays. The use of adult corals (measuring growth rates, fecundity, and symbiotic associations) as well as their gametes and larvae as ecological indicators addresses the concern that mortality is a crude measure of environmental stress. Determining and measuring sublethal effects allow for a more proactive approach to monitoring and management.

Zooxanthellae loss

One oft-cited response of zooxanthellate reef organisms to a variety of stresses (both natural and anthropogenic) is the expulsion of symbiotic zooxanthellae, or "bleaching" (e.g., Gates and Brown 1985). As this phenomenon is both widespread and easily measured in a quantitative fashion, Brown (1988) and Jones (1997) have suggested that bleaching can serve as an excellent bioassay for assessing environmental stress on corals. Unfortunately, although zooxanthellae loss is a sensitive, sublethal response of corals to a wide range of environmental stressors (including temperature and salinity fluctuations and marine pollution), it is precisely this lack of a response specificity which limits its usefulness in bioassays.

Research recommendation: Bleaching may provide an early indication of stressful conditions upon a reef, but additional bioassays must be employed in order to identify the specific nature of the stressor and thus initiate corrective management actions.

Coral diseases and cyanobacterial blooms

Similar to the abovementioned indicator of zooxanthellae loss, monitoring the frequency and severity of occurrences of coral diseases has been proposed as an important metric of reef health (Richardson 1995). Particularly in the Florida Keys and Caribbean reef province as a whole, coral diseases such as black, white and red band disease are thought to have played an important role in reef degradation. Similarly, cyanobacterial blooms in the Florida Keys have been observed to completely cover large areas of reef, leading to the eventual death of the original benthic cover, especially the soft corals and gorgonians (Richardson 1995). Unfortunately, the causal factors involved in coral diseases and cyanobacterial blooms are poorly understood, though circumstantial evidence suggests that eutrophication may play a role, especially in cyanobacterial blooms. Nonetheless, incidence of coral diseases and algal/bacterial blooms are certainly an indicator of coral health, and clearly merit consideration for inclusion in biocriteria guidelines.

Research recommendation: Current research is focusing on determining the causal agents of coral diseases, as well as the relationship of disease incidence to surrounding water quality (Richardson 1995). Results from this research should determine the ultimate utility of these potential bioindicators. Further work should also focus on developing a standardized protocol for measuring incidence and severity of diseases and blooms, as well as interpretation of results.

Bioaccumulation of metals, phosphorus in coral skeletons

A final coral-based bioassay relies upon the bioaccumulating function of hard coral skeletons. A number of studies have revealed the tendency of hard corals to incorporate seawater contaminants such as trace metals and phosphorus into their skeletons during normal growth (Dodge *et al.* 1984, Brown 1988, Hanna and Muir, 1990). These studies have demonstrated that corals incorporate these contaminants in proportion to their ambient concentrations in the surrounding seawater, suggesting corals may be faithful long-term recorders of environmental water quality. Note, however, that at least one study (Brown and Holley 1982) found no apparent metals bioaccumulation by corals on an impacted reef flat where other organisms showed significant metal accumulation in tissues. Those authors suggest that one reason for the apparent discrepancy involves differences in the bioavailability of metals to the corals and other organisms; trace metals in solution in seawater undoubtably have different uptake routes than metals in particulate form. Even in those studies where corals did accumulate metals, an important complication is the finding that different species of coral from the same site demonstrate different uptake rates of trace metals (e.g., Hanna and Muir 1990). This finding suggests an active metabolic role of corals in the uptake of contaminants as opposed to simple passive uptake at ambient concentrations. Given this, it seems altogether possible that different individuals of the same species, living in different ambient conditions (with regard to depth, wave exposure, etc.) may also demonstrate different uptake rates of contaminants.

Research recommendation: While this bioaccumulation assay shows promise for reef water quality monitoring, it is apparent that further research is needed for a thorough understanding of the process of contaminant uptake by coral skeletons (including differences in the uptake of soluble and particulate fractions) and subsequent calibration of the skeletal signal to ambient water concentrations of the contaminant in question.

Physical damage

Jameson *et al.* (1997) in their rapid ecological assessment of 48 diving sites in the Egyptian Red Sea used quantitative line intercept transect data and qualitative quadrate data to evaluate physical damage before mooring buoys were installed. Baseline data from 1987 (Riegl and Velimirov 1991, Riegl and Velimirov 1994) was used as a yardstick to create the Reef Quality Index (a measure of acceptable coral reef aesthetic quality - not reef "health"). Diving sites did not meet acceptable standards for aesthetic quality if hard coral cover was < 30%, recently broken coral was > 5%, recently dead coral was > 3%, and rubble was > 5%. Unacceptable dive sites were then candidates for detailed monitoring and if necessary selected for recuperation or restoration programs.

Other researchers have used physical damage studies to estimate diving carrying capacities for coral reef ecosystems (Hawkins and Roberts 1996, Chadwick-Furman 1996, Dixon et al. 1993).

Research recommendation: In these types of studies one is never sure of the exact cause of physical damage (anthropogenic vs. nonanthropogenic). Reliable methods for controlling experimental conditions need to be developed. Historical baseline data also needs to be available to create an accurate and realistic Reef Quality Index.

3.4.2 Non-Coral Bioindicators

While a number of the above mentioned coral-based bioassays show strong potential, and the importance of including coral parameters in any reef monitoring program is irrefutable, a growing number of workers have advocated reef assessments which are more taxonomically-comprehensive in scope. Harger (1995) implores that "there is more to coral reef ecosystems than corals and fish," while Dustan and Hallas (1987) urge a "less myopic view of the reef" than is commonly taken in most coral monitoring schemes. The value of such "expanded" coral reef surveys was recently underscored in a large-scale assessment of the Kepulauan Seribu reefs near Jakarta, Indonesia where inclusion of stomatopod crustacean surveys in the monitoring protocol was instrumental in suggesting the cause of the drastic reduction in live coral observed (Erdmann and Sisovann, in press).

Erdmann and Caldwell (1997) list a number of non-coral bioindicators which have been proposed, formally or otherwise, for inclusion into reef monitoring programs worldwide. Many of the proposed reef bioassays are "borrowed" from successful temperate marine bioassessment programs, though they are often not as well-developed. Others are taken from primary literature reports, which often suggest the bioassay potential of various organisms which seem particularly affected by various anthropogenic impacts on reefs. In general, coral reef bioassessment is still in its infancy, lagging far behind the programs developed for aquatic and temperate marine biomonitoring. Nevertheless, many of the proposed non-coral bioindicators show great promise, as discussed below. A brief evaluation of each with respect to the bioindicator selection criteria in section 3.4 should help direct future research efforts to refine these indicators into useable bioassays.

Butterflyfish

Undeniably, the most widely-discussed (and often misunderstood) bioindicators of environmental stress on coral reefs are the chaetodontids or butterflyfish, which have now been incorporated into a number of reef monitoring programs in the Indo-Pacific (Nash 1989, White 1989, Crosby and Reese 1996). Reese (1981) first gave a detailed definition of the butterflyfish bioindicator hypothesis, which has been re-stated again in Hourigan et al. (1988), Reese (1994), and Crosby and Reese (1996). In summary, this hypothesis states that for those species of butterflyfish which are obligate corallivores, a decline in the condition of a coral reef, manifested by decreasing food quality of the stressed coral polyps, will result in a decrease in the abundance and diversity of these species and an increase in territory size, feeding rate and agonistic encounters as mated pairs attempt to maintain their nutritional intake by expanding their territories to include more coral colonies. After a time, feeding rates may actually decrease as more time is spent defending territories from neighboring pairs.

Since the hypothesis was first published, a number of studies have shown a positive correlation between chaetodontid diversity and abundance and percent live coral cover (but not decreasing food quality of the stressed coral polyps) or coral species richness (e.g., Bell and Galzin 1984, Bouchon-Navaro et al. 1985, White 1989; but see Roberts and Ormond (1987) for conflicting evidence).

The often misunderstood aspect of the technique (which is not elucidated in Crosby and Reese 1996) is that: "the early warning function of the butterflyfish bioassay was never intended to be a direct indication of specific measured environmental stresses such as specific toxins" (Crosby, personal communication).

As such, the technique as presently outlined (Crosby and Reese 1996), is useful as a preliminary screening mechanism that could trigger more detailed studies to determine the specific cause of the decreasing food quality of the stressed coral polyps.

On a precautionary note, butterflyfish populations are sometimes subject to intensive human exploitation; not only are they favorite targets of marine aquarium collectors, they are often sought as food-fish in many developing countries (Erdmann 1997a). For this reason alone they are included in the Reef Check monitoring protocol - not as bioindicators of reef health, but as indicators of aquarium-collecting pressures (Hodgson 1997). Mechanisms must be incorporated into monitoring programs to insure that butterflyfishes are adequately protected from harvest and exploitation.

Research recommendation: To date, no research has yet quantitatively shown effects on butterflyfish abundance, diversity, feeding rate, territory size or aggressive encounters as a result of a specific chronic, sub-lethal stressor on hard corals. This and other concerns have led a large number of workers to question the relevance and utility of the butterflyfish bioassay (Roberts and Ormond 1987, Roberts et al. 1988, Brown 1988, Jones and Kaly 1996, Erdmann 1997a, Erdmann and Caldwell 1997).

To develop the butterflyfish bioassay into a response specific technique (i.e. take it beyond the preliminary screening tool phase) we recommend the following.

1. The "early warning" function of the butterflyfish bioassay needs to be substantiated. Although the butterflyfish bioindicator hypothesis suggests that sublethal degradation of coral reefs (manifested as decreasing food quality of the stressed coral polyps) can be detected by changes in the behavior and abundance of obligate corallivorous chaetodonts, available published data shows only correlations between chaetodont abundance and percentage live coral cover. To be of use to reef management programs, the bioassay must be able to detect such sublethal deterioration before a reduction in live coral cover occurs. If butterflyfish provide no early warning function before reductions in live coral cover occur, then one might as well directly monitor live coral cover.

2. The response specificity of the butterflyfish bioassay must be calibrated. Presently, if butterflyfish are simply responding to a reduction in live coral cover or food quality of coral polyps, monitoring their populations provides no insight into the specific stress causing these changes.

3. Following the above two points, the butterflyfish bioassay will also need a framework (statistical or numeric index-based) for interpreting the results of monitoring.

Ectoparasites on coral reef fishes

Evans *et al.* (1995) further suggest that measurement of the incidence of parasitism on coral reef fishes can provide an indirect measure of water quality conditions surrounding coral reefs. Previous authors have suggested that incidence of parasitism and/or disease may increase in "stressed" organismal populations (Esch *et al.* 1975, Gray 1989). In a study on the incidence of the isopod ectoparasite Renocila sp. on the coral reef fish Abudefduf saxatilis under varying pollution regimes, Evans et al. (1995) found weak evidence that parasite load was higher at heavily polluted sites than at less polluted sites.

Erdmann (1997b), however, examined the incidence of the gastropod ectoparasite Caledoniella montrouzieri on reef flat stomatopod assemblages in Indonesia and found no significant differences in parasite load between stomatopod assemblages at heavily polluted sites and relatively pristine sites. He suggested that some parasites, especially those with direct host transmission, may require high population densities of their host organisms for successful transmission. Host organisms which are sensitive to pollution and demonstrate reduced abundance under polluted conditions would therefore be unlikely to show increased incidence of parasitism with increasing pollution.

Other authors studying fish disease in polluted marine areas (e.g., McVikar et al. 1988) likewise suggest no clear correlation between pollution and incidence of disease/parasitism, and both Esch *et al.* (1975) and Gray (1989) conclude that the evidence for such a connection is equivocal at best.

Research recommendation: More evidence suggesting no clear correlation between pollution and incidence of disease/parasitism suggests this is not a potential bioindicator and would not warrant further consideration. However, research has not been extensive and further investigation may be fruitful.

Larval assemblages of fish and other reef taxa

One result of the stomatopod bioindicator work which appears to be common to similar studies on other reef organisms is the apparent extreme sensitivity of the larval and postlarval stages to water quality deterioration (Erdmann 1997b). This result has been reported by other workers for stomatopods (Gajbhiye et al. 1987), spiny lobsters (Herrnkind *et al.* 1988), and reef-flat gastropods (Garrity and Levings 1990). Likewise, Doherty (1991) proposes that the environmental sensitivity of larval coral reef fish assemblages makes them ideal candidates for reef biomonitoring studies.

Research recommendation: This suggestion obviously requires substantial additional research before larval fish assemblages can be used in an effective bioassay, but the broader implication here is that biomonitoring of a wide variety of reef organism larval and postlarval stages may prove an extremely sensitive method of detecting water quality deterioration. Future research efforts on reef bioindicators should certainly address this potential. An important obstacle to larval bioassays is the difficulty of reliably and quantitatively sampling larval assemblages (Erdmann 1997b). Doherty (1991) overcomes this problem by using expensive automated light traps, but these may well be outside the scope of most monitoring programs' budgets.

Indicators of Fishing/Shell Collecting

Both the Reef Check and ICLARM Aquanaut volunteer reef surveys include a number of "indicator species" of direct human exploitation of coral reefs in the form of fishing and collecting pressures (Hodgson 1997, McManus et al. 1997). Examples include edible holothurian species (trepang), giant clams (Tridacna sp.), mother-of-pearl shells (Trochus sp.), butterflyfishes (Chaetodontidae), large food fishes (e.g., Serranidae, Haemulidae) and spiny lobster (Panulirus sp.).

Research recommendation: While no formal interpretative framework is provided for assessing the results of monitoring the abundances of these groups, the intuitive appeal of indicators of fishing/collecting pressure suggests that this approach is worthy of further development for more rigorous use.

Organic contaminants and the development of fishes

Ongoing graduate work on Johnston Atoll by Lisa Kerr (personal communication) involves quantifying the effects of organic contaminants on the development of fishes. Kerr is trying to develop the use of the occurrence of developmental defects in a demersal spawning fish as a bioindicator of pollution effects. She has been studying colonies of the damselfish Abudefduf sordidus in areas contaminated with PCBs and will also be looking in areas contaminated with dioxins. Kerr's preliminary data suggests that with increasing sediment PCB concentration there is an increase in the occurrence of developmental defects. Her current study will track effects in the offspring of individual fish and then relate the level of effects in individuals to the individual's contaminant body burden.

Research recommendation: Contingent upon ongoing research results.

Bioaccumulation in molluscs and macrophytes

Bioaccumulation of trace metals and phosphorus by hard coral skeletons has been previously discussed, but several non-coral organisms have also been proposed as bioaccumulators of marine pollutants impinging on coral reefs. Specifically, Brown and Holly (1982) examined metals bioaccumulation by a macrophytic alga (Padina tenuis) and several molluscs, including the bivalves Saccostrea cucullata and Isognomon isognomon and the gastropod Nerita chamaeleon, on a reef flat affected by tin dredging and smelting. Their results showed that specimens of both bivalve species from the affected reef had elevated metals levels in their tissues relative to specimens from control sites, whereas the alga and the gastropod tissues showed no such clear pattern.

As discussed above, these authors suggest that differences in bioavailability of the metals (mostly in particulate form in this study) account for the differences between organisms: the filter-feeding bivalves consumed the metallic particulates, whereas the alga (and hence the herbivorous algal-feeding gastropod) were unaffected. Though additional studies of bioaccumulators are rare in the coral reef literature, temperate analogs of each of these organisms have been used extensively in bioassays worldwide (Bryan and Hummerstone 1973, Goldberg et al. 1978, Hungspreugs and Yuangthong 1984, Phillips 1994).

Two further issues involve the expense and relevancy of these bioassays. Chemical analysis of tissues for metals concentrations requires substantial money and equipment, two resources which small-scale monitoring programs may find in short supply. Furthermore, there is always the question of whether the pollutants being accumulated are even considered detrimental to reef health. Obviously, bioaccumulation assays should be limited to monitoring those pollutants with known impacts on coral reefs.

Research recommendation: While the same issues of calibration, bioavailability and differences in uptake mentioned above for coral bioaccumulators apply here, with further development these bioassays may be useful in some reef monitoring contexts as well.

Sessile reef organisms (sponges, gorgonians)

Alcolado *et al.* (1994) have suggested taxonomically-expanded surveys of the sessile reef community as an effective means of monitoring environmental conditions on reefs. These authors propose the use of two well-known diversity indices, H' (Shannon-Weaver heterogeneity index; Shannon and Weaver 1949) and J' (Pielou's evenness index; Pielou 1966), to evaluate environmental stresses on three groups of sessile reef taxa (scleractinians, gorgonians, and sponges). Specifically, they propose that calculation and comparison of H' and J' for each of these three taxonomic groups allows a rough classification of the environmental conditions faced by organisms on a particular reef. The environmental classification scheme proposed ranges from "favorable and predictable" (high values of both H' and J') to "unpredictably severe" (low values of both H' and J'). Using sponge communities in Cuba, the authors have developed and calibrated a numerical index for interpreting the various values of these diversity indices which they claim reliably segregates polluted reef stations. Unfortunately, the details of these investigations are reported in Cuban journals which were unavailable to the authors, preventing a detailed review of this technique.

Research recommendation: Although several workers (e.g., Green and Vascotto 1978) have argued against the use of diversity indices in water quality assessment, this technique appears worthy of further investigation. Potential issues regarding its appropriateness include questions about the early-warning function and response-specificity of the bioassay, as well as problems of taxonomic resolution (especially in the hyper-diverse Indo-Pacific).

Heterotrophic macroinvertebrates

Another promising, but largely undeveloped, set of bioassays of reef condition have been proposed based upon the well-documented ecosystem shift which has occurred on many reefs in urban, polluted areas. A number of workers have described a distinctive shift in pollution and sediment-stressed reefs from those dominated by coral-algal symbionts and reef fish towards those dominated by heterotrophic macroinvertebrates, especially scavengers, filter feeders, deposit feeders and internal bioeroders (Tomascik and Sander 1987a, Kinsey 1988, Tomascik *et al.* 1994, Risk et al. 1994). Organisms which are reported to have increased dramatically in abundance include zoanthids, sponges, barnacles, crabs, hydroids, tunicates, bioeroding (boring) sponges and bivalves, as well as a range of echinoid, holothurian and crinoid echinoderms (Dahl and Lamberts 1977, Dahl 1981, Dustan and Halas 1987, Kinsey 1988, Tomascik *et al.* 1994, Risk et al. 1994, Vail in press).

Abundance measures of a number of these taxonomic groups are already included in several reef monitoring programs (e.g., Dahl and Lamberts 1977, Dahl 1981, Risk et al. 1994, McManus et al. 1997, Hodgson 1997), apparently based upon the assumption that increases in abundance of these groups may indicate deteriorating environmental conditions on the surveyed reef.

Research recommendation: While these various organisms may very well prove to be excellent bioindicators of water quality deterioration, the sensitivity of their response has not yet been fully investigated and described. Clearly, the development and calibration of these potential bioassays should be a research priority. Data collected in the Reef Check and Aquanaut programs should also provide further evidence of the value of a number of these bioindicators.

Internal bioeroders

Of the above mentioned eutrophication bioindicators, one group, internal bioeroders, have been thoroughly investigated and have demonstrated a consistent, graded response of increasing abundance with increasing eutrophication on reefs (Rose and Risk 1985, Sammarco and Risk 1990, Risk *et al.* 1995, Holmes 1997). Holmes (1997) found that the proportion of dead coral rubble invaded by clionid sponges, as well as the number of invasions per rubble sample, increased dramatically with increasing eutrophication on reefs of Barbados. Rose and Risk (1985) found similar results with Cliona infestations of live Montastrea cavernosa heads in the Grand Caymans, while Sammarco and Risk (1990) and Risk *et al.* (1995) suggested that distinctive cross-continental shelf patterns of bioerosion (by sponges and bivalves) in Porites and Acropora on the Great Barrier Reef were explained primarily by increasing organic input with proximity to the mainland.

Research recommendation: Though this group has not yet been formally proposed for inclusion in biomonitoring programs, results of the above research suggest that internal bioeroders provide a sensitive assessment of increasing eutrophication on reefs and that development of a rigorous bioassay could be accomplished with minimal additional research.

Coelobites

Choi (1982) proposed that coelobite communities (reef cavity-dwellers such as foraminifers, bryozoans, tunicates, molluscs, sponges and serpulid worms) also respond in a sensitive manner to environmental stress, though in an opposite manner from that of internal bioeroders. His study on the effects of offshore drilling on coral rubble-dwelling coelobite communities showed a dramatic decrease in abundance of coelobites with proximity to the well-head, which he suggests is an effect of the greater concentration of drilling discharges close to the well-head. Drilling discharges were postulated to affect coelobites by direct smothering and/or iron toxicity.

In order to characterize the effects on community structure, Choi developed a numerical index whereby he assigned points to each community (rubble piece) sampled based upon the presence/absence and abundance of various coelobite groups. Using the results of his study, he calibrated the index and assigned interpretive meanings to various scores (e.g., scores of 10 or higher indicate a "healthy" or "recovering" coelobite community). While the widespread applicability of this bioassay has yet to be demonstrated (offshore drilling is a relatively uncommon stress to reefs), it may have potential for monitoring sedimentation stress on reefs. The method is particularly noteworthy in that it is one of the only examples of a calibrated numerical index of reef community health.

Research recommendation: Further research should focus on determining the sensitivity of this response relative to the hard coral community response to sedimentation (i.e., does it provide an early warning of increasing sedimentation, or is this parameter more easily measured by simple sediment traps?).

Foraminifers

Foraminifera are typically important contributors to reef sediments, especially species of larger foraminifera that host algal endosymbionts. Foraminiferal assemblages in reef sediments have been widely studied since 1922 primarily for the purpose of using analogies with modern biotas to interpret fossil assemblages and paleoenvironments for petroleum exploration. They are also easy and inexpensive to collect.

Cockey *et al.* (1996) show that published accounts of foraminiferal assemblages from sediments collected 30 or more years ago can be valuable resources in efforts to determine if biotic changes have occurred in coastal ecosystems and that family level identifications may be sufficient to detect decadal-scale changes in foraminiferal assemblages in reef sediments. Models formulated by Hallock and Schlager (1986), Birkeland (1987, 1988), and Hallock (1988) predict that community response to gradually increasing nutrient flux, whether natural or anthropogenic, should favor phytoplankton, benthic algae, and heterotrophic taxa lacking algal symbionts, rather than taxa that utilize algal symbionts for enhanced growth and calcification. Benthic succession along a nutrification gradient is a predictable response (Pearson and Rosenberg 1978) that has been commonly observed in foraminiferal assemblages (Lidz 1966, Alve 1995, Schafer *et al.* 1995). Pacific benthic foraminiferal assemblages have been observed to shift from predominantly algal symbiont-bearing species to dominance by small species lacking algal symbionts in response to a limited anthropogenic nutrient source (Hirschfield et al. 1968). Cockey *et al.* (1996) discuss how changes in foraminiferal assemblages, from dominance by algal symbiont-bearing taxa in 1959-1961 to heterotrophic taxa in 1982-1992, are consistent with predictions of benthic community response to gradually increasing nutrient flux into South Florida's near coastal waters by Szmant and Forrester (1996). The paucity of eutrophication-indicating foraminiferal taxa in sediments off Key Largo supports previous studies that show that anthropogenic nutrient influx has not caused eutrophication of reef and open-shelf environments in that area. Hallock et al. (1993a) predicted that at least a 10-fold increase in nutrients resources would be required to cause eutrophication in habitats occupied by mixed coral-algal communities in the Florida Keys.

Research recommendation: The use of foraminifera as bioindicators is very promising and new research should focus on creating and calibrating a multimeric index.

Stomatopod crustaceans

Stomatopod crustaceans were first proposed as bioindicators of marine pollution stress after a study on the effects of the 1986 Galeta, Panama oil spill indicated that these benthic reef-dwellers were highly sensitive to oil pollution (Jackson *et al.* 1989, Steger and Caldwell 1993). The results of that study showed that reef-flat stomatopods responded to heavy oiling by an initial, drastic decrease in abundance, followed by an extended period of reduced recruitment.

Based on these initial results, an evaluation of the bioindicator potential of Indonesian reef-flat stomatopod communities was initiated. The results of that 3-year study confirmed that stomatopod abundance, diversity and recruitment are strongly negatively correlated with sediment concentrations of petroleum hydrocarbons and selected heavy metals, and with surrogate measures of sewage and agrichemical runoff (Erdmann 1997b). In general, stomatopod communities show a strong trend of decreasing abundance and diversity with increasing proximity to major human population centers (Erdmann and Caldwell 1997, Erdmann and Sisovann in press). In addition to their demonstrated sensitivity to water quality degradation, stomatopods are abundant and ubiquitous throughout the world's reef provinces, and their taxonomy is readily taught to non-specialists. Reef-flat stomatopod assemblages in particular can be sampled quantitatively without the use of SCUBA, making them ideal candidates as inexpensive, low-tech bioindicators of reef water quality degradation.

Research recommendation: A further two-year project has recently been initiated with the goal of distilling the above results into a multimeric index of coral reef integrity, using as a model the successful benthic index of biotic integrity (B-IBI) developed for Tennessee Valley Authority bioassessment programs (Kerans and Karr 1994). The index will then be further calibrated based upon the results of comparative studies in 5 other regions of Indonesia (Erdmann in prep.). It is anticipated that the finalized stomatopod biomonitoring protocol will be completed in time for presentation at the 9th International Coral Reef Symposium in 2000 in Bali, Indonesia.

Amphipods

Because of their ecological importance, numerical abundance, and sensitivity to a variety of toxicants and pollutants, amphipod crustaceans have long been known as sensitive environmental indicators (Hart and Fuller 1979, Thomas 1993). Oakden et al. (1984) showed experimentally that temperate phoxocephalid amphipods actively avoided sewage and trace metal-contaminated sediments, preferring instead to burrow in "clean" sediments. Lacking a pelagic larval stage, amphipods are benthic recruiters, thereby minimizing dispersal effects. They show a high degree of habitat specificity and niche requirements and are one of the major benthic components in tropical marine ecosystems worldwide, in terms of biomass and species diversity.

The use of amphipods in environmental monitoring has been limited to the few temperate regions where long-term taxonomic and natural history investigations have been undertaken. California currently uses amphipods as primary biological monitors at sewage outfalls. Monitoring programs incorporating amphipods have been used to assess the environmental effects of oil spills in the Persian Gulf, Alaska, and Panama. California and the Environmental Monitoring and Assessment Program (EMAP) program of EPA have designated several species of amphipods as bioassay organisms for sediment toxicity tests in soft-bottom environments (USEPA 1990b). Amphipods are so useful as bioindicators that US Government agencies now require their identification to the species level in permitting operations such as oil leases and outfalls. Their incorporation into bioassessment programs is dependent upon completion of comprehensive coastal resource inventories and taxonomic surveys (Thomas 1993).

In addition to acute and chronic sensitivities to pollutants and toxicants, amphipods exhibit a number of altered behavioral responses to sublethal levels of a variety of compounds that can cause reduction or elimination of the population (Baker 1971, Sandberg et al. 1972, Percy 1976, Linden 1976a & b, Lee et al. 1977). Amphipods are more sensitive than other species of invertebrates (decapods, polychaetes, molluscs, and asteroids) to a variety of contaminants (Ahsanullah 1976, Swartz et al. 1985, Swartz 1987). Amphipods also show responses to dredging, shoreline alteration, fishing practices, and changes in salinity and dissolved oxygen (Barnard 1958 & 1961, McLuskey 1967 & 1970, Widdowson 1971, Vobis 1973). In freshwater streams of Germany, the onset and recovery of 'stream souring' (acidification) has been documented since 1945 on the basis of distribution patterns of three species of the amphipod genus Gammarus (Meijefing 1991). This biological model has proved to be a more responsive and sensitive measure of environmental conditions than standard water quality protocols (Meijering 1991).

Ecological factors must also be considered in evaluating the potential information value of various amphipod groups. For example, in measuring the effects of an oil spill in a coral reef system, cryptofaunal and infaunal species of invertebrates may yield different patterns. Epifaunal forms could 'raft' in, while infaunal and cryptofaunal forms would have to recruit along the bottom from unaffected or minimally-impacted areas. Thus, the observed recolonization rates of the two groups, and subsequent interpretation of effects, could be quite different (Thomas 1993). In an actual oil spill on a Panama coral reef, two infaunal peracarid crustaceans (amphipods and tanaids) showed virtually no recovery after a 9-month period (Jackson *et al.* 1989), while other groups, including other crustaceans (brachyurans and burrowing shrimp), showed significant recovery at the same sites.

Research recommendation: Potential for amphipods as bioindicators exists in a wide variety of environments, especially in coral reefs, but their incorporation into such programs is dependent upon completion of taxonomic surveys and inventories.

Gastropod imposex

A well-substantiated bioassay with extreme sensitivity and response specificity is the evaluation of gastropod imposex as an indicator of tributyltin pollution in marine ecosystems around the world (Ellis and Pattisina 1990, Foale 1993, Gibbs and Bryan 1994). Imposex is the imposition of male sexual characteristics on female marine snails; its occurrence in snail populations generally signals exposure to tributyltin, an extremely toxic biocide which is still used in antifouling paints in a number of developing countries lacking strong environmental protection laws. Imposex as a result of tributyltin exposure (often at concentrations below the limits of chemical analytical detection) has been reported from over 45 species of neogastropod, including reef-associated species of the genera Thais and Vasum (Ellis and Pattisina 1990, Evans et al. 1995).

The occurrence and severity of imposex in a particular population is usually quantified using both frequency of imposex in females and the relative penis size index (RPS Index), calculated by dividing the mean ratio of penis weight to body weight for all females sampled by the mean ratio for the males (Foale 1993; note that other authors - e.g., Ellis and Pattisina 1990 - use penis length in calculating the RPS index instead). In populations which have not been exposed to tributyltin, both the frequency of female imposex and the RPS index is expected to be zero (or nearly so), as unaffected females do not normally develop a penis. In populations with tributyltin exposure, the frequency of imposex often reaches 100%, at which point the RPS index is necessary to differentiate the severity of exposure between populations (Ellis and Pattisina 1990).

Research recommendation: In monitoring situations where tributyltin exposure is a concern, measurement of gastropod imposex is a fully-developed bioassay with proven applicability to coral reef systems. The protocol is fast, inexpensive, and the results are easily interpreted. The only potential problem with its use can be the collection of sufficient sample sizes of the snails, which typically prefer "rocky shore" habitats (Evans et al. 1995).

Corallivores

Both of the above mentioned monitoring programs also advise recording abundances of corallivores such as the crown-of-thorns starfish (Acanthaster planci) and Drupella gastropods, which in "outbreak" situations have caused severe reef destruction on many reefs throughout the Pacific (Birkeland and Lucas 1990, Turner 1994). Though the proximal causes of outbreaks of these predators are still vigorously debated, their obvious relation to "reef health" makes them a logical choice in monitoring as well.

Research recommendation: Further research is obviously required to develop and calibrate a bioassay involving these corallivores.

Nitrogen isotope ratios and coprostanol levels in reef organism tissues

Although not a bioindicator per se, Risk *et al.* (1994) and Dunn (1995) have suggested the determination of stable isotope ratios of $^{15}N/^{14}N$ (denoted d ^{15}N) in reef organism tissues as an excellent means of specifically evaluating the input of human faecal wastes into reef ecosystems. In studies in Zanzibar and the Maldives, tissues of reef corals from sites with heavy human sewage inputs showed significantly higher d ^{15}N values than coral tissues from relatively "clean" sites (Risk *et al.* 1994).

This technique is based upon the stepwise enrichment of $^{15}N/^{14}N$ ratios along increasing trophic levels, which is caused by the preferential elimination of the lighter isotope ^{14}N in urine and excretion products and the resulting d ^{15}N increase in organism tissues and faeces (reviewed in Peterson and Fry 1987). The technique is further predicated on the hypothesis that coral reef trophic structures with differing levels of sewage inputs will reflect these differences in the d ^{15}N

signal at each trophic level. Those reefs with minimal sewage input should exhibit relatively low d ^{15}N values at each trophic level, indicative of oligotrophic conditions where algal fixation of atmospheric N (d ^{15}N=0 by definition) is the major source of nitrogen. Conversely, those reefs which are strongly impacted by inputs of human faecal matter should show enriched d ^{15}N values, as a result of utilization of the relatively high d ^{15}N fecal matter as a primary nitrogen source at the base of the trophic structure.

Additional studies currently being conducted on corals in Java and Sulawesi, Indonesia, have substantiated the above results from Zanzibar and the Maldives (Risk personal communication). Extension of the technique to other reef organisms has proved successful as well. Risk and Erdmann (in press) report that stomatopod tissues from the Spermonde Archipelago in Sulawesi show a dramatic, logarithmic increase in d ^{15}N with increasing proximity to Ujung Pandang, a coastal city of over one million residents with no primary sewage treatment.

Research recommendation: Continuing research on this bioassay, including comparative work in a number of different regions with varying human population levels, should result in the eventual calibration of a d ^{15}N index of sewage impacts on coral reefs. The technique has the disadvantage of requiring expensive analytical equipment (mass spectrophotometer), but the extreme sensitivity and replicability of results suggest that this assay could have widespread applicability with a number of reef taxa. In the Zanzibar/Maldives study, Risk *et al.* (1994) also suggested analyzing coral tissues for high concentrations of the sterol coprostanol, a breakdown product of cholesterol and hence a potential chemical indicator of human faecal waste. Results from coral sampling in the Maldives were inconclusive, but further research on this method is ongoing (Risk *et al.* 1994).

Changes in soft-bottom benthic community structure

Though not yet formally applied to coral reef ecosystems, a final set of bioassays worthy of mention are based on a large body of work examining pollution-induced changes in macrobenthic community structure in temperate soft-bottom communities. Extensive work by Pearson, Gray, Warwick, Clarke and associates has demonstrated a number of consistent, predictable responses in soft bottom community structure to increasing pollution, including a decrease in species richness, an increase in the total number of individuals due to a "retrogression to dominance by a few opportunistic species", a reduction in the mean size of the average species or individual, changes in the shape of the log-normal distribution of individuals among species, and increased variability in species diversity indices such as H' (Pearson and Rosenberg 1978, Gray and Mirza 1979, Gray 1981 & 1989, Pearson *et al.* 1983, Warwick 1986, Clarke 1993, Warwick and Clarke 1993, but see Weston 1990 for contradictory evidence).

Brown (1988) has suggested that the above models may be inappropriate for coral reefs, as these habitats are much more highly-structured than soft bottom communities and thus may respond very differently. Nonetheless, the results of Tomascik and Sander's (1987a) study on eutrophication effects on coral community structure correspond in part with this model, while a similar study by Clarke *et al.* (1993) demonstrates a breakdown in "seriation" (zonation pattern) in coral assemblages subject to sedimentation.

Research recommendation: A concerted research effort to apply the soft-bottom models to coral reef communities is clearly warranted. Furthermore, Brown (1988) suggests that even if these bioassays prove unworkable in a coral reef context, they may still be applicable to the soft-bottom communities which are often adjacent to coral reefs (lagoon bottoms and the base of reef slopes). An important consideration in applying the soft-bottom models to coral reef communities is that these models are based on *community* response to pollution. Coral reef studies tend to be more narrowly-focused, for example on *assemblages* of scleractinians or coral reef fish. Narrowing the taxonomic focus in studies of pollution effects may preclude detection of changes in the broader reef community (e.g., a decrease in coral cover with a corresponding increase in tunicate and sponge abundance). The difficulties in examining response of the entire community in highly diverse coral reef habitats may prevent the application of the soft-bottom bioassays to reef systems and is worthy of careful consideration.

FACT‘97 coastal indicators

FACT is structured around nine strategic issues judged to be critical to the future of Florida's coast over the next 20 years (Bergquist *et al.* 1997). These broad strategic issues were refined into two-to-four sub-issues or components of each issue. These sub-issues then became the final framework around which indicators were developed. The nine issues and their associated sub-issues are as follows.

1. **Impact of Growth in the Coastal Zone**
    - Impacts of Population Growth
    - Patterns of Development
    - Sufficiency of Infrastructure
    - Economic Impacts
2. **Disruption of Coastal Physical Processes**
    - Alteration of Existing Natural Systems
    - Construction of Altering Structures
3. **Responding to Coastal Threats and Hazards**
    - Coastal Hazard Mitigation
    - Incompatible Living Areas
    - Industrial Impacts
4. **Degradation and Restoration of Coastal Ecosystems**
    - Habitat Change
    - Species Population Trends
    - Water Quality Trends
5. **Managing Fresh Water Allocation**
    - Fresh Water Allocated for Ecological Maintenance
    - Fresh Water Allocated to Meet Residential Needs
    - Fresh Water Allocated to Meet Commercial/Industrial Needs
    - Fresh Water Allocated to Meet Agricultural Needs

6. **Sustaining the Human Uses of the Coast**

    - Maintenance of Recreational Value
    - Sustainable Economic Use
    - Balancing Development with Coastal Resources

7. **Balancing Public and Private Uses of Resources**

    - Private Property Issues (no indicators have been developed for this sub-issue)
    - Stewardship of Coastal Resources

8. **Preservation of Cultural and Aesthetic Resources**

    - Preservation of Archaeological and historical Resources
    - Preservation of Living Resources
    - Conservation of Coastal Open Space

9. **Encouraging Public Awareness and Involvement**

    - Public Awareness
    - Public Participation

Research recommendation: The change in coral reef community dynamics indicator used by FACT is the coral reef/hard bottom monitoring facet of the FKNMS water quality monitoring program (Table 3.3). Relating other FACT indicators to coral reef ecosystem integrity will require the development of special indices and calibration.

Map-based indicators of potential threats to coral reef ecosystems

The World Resources Institute, in collaboration with the International Center for Living Aquatic Resources Management, the World Conservation Monitoring Center and the United Nations Environment Programme and a host of other coral reef experts, has created a system of evaluating potential threats (not actual reef condition) to coral reef ecosystems using map-based indicators (Burke et al. 1998). Results are based on a series of distance relationships correlating mapped locations of human activity, such as ports and towns, oil wells, coastal mining activities and shipping lanes (component indicators) with predicted risk zones of likely environmental degradation. Detailed sub-national statistics on population density, size of urban areas, and land cover type were also incorporated into the analysis. Data on rainfall and topography are used to estimate potential runoff within watersheds, from inland deforestation and agriculture. While still experimental, the "Reefs at Risk" indicators flag problem areas around the world where - in the absence of good management - coral reef degradation might be expected, or predicted to occur shortly, given ongoing levels of human activity.

Research recommendation: To make these indicators approach reality, a time factor must be incorporated into them, otherwise there is no feeling of urgency to the threats. Some of the map-based indicator assumptions need work as they are confounded by other factors or simply invalid.

Rapid assessment of management parameters (RAMP) for coral reefs

The University of Rhode Island's Coastal Resources Center (CRC) in collaboration with the International Center for Living Aquatic Resources Management (ICLARM) RAMP designed and field tested a set of indicators for assessing the human impacts (social, cultural and economic) on coral reefs. Indicators are organized according to proximity to the designated reef (e.g., national, regional and local), context (political, socioeconomic and cultural), reef uses (fishing, mining, tourism/recreational, etc.), and governance (institutional frameworks, knowledge bases, plans, implementation, monitoring and evaluation). A guide for information acquisition and subsequent coding for inclusion in ReefBase was also developed (Pollnac, 1997).

Research recommendation: Used together, RAMP and ReefBase have the potential to provide a baseline for monitoring changes in coral reef ecosystems as well as a standardized database for exploring interrelationships between the variables included. Defining and recording a standardized set of indicators is of critical importance. Presently, coastal zone and fisheries management literature is characterized by case studies conducted by many different individuals with unknown biases and varying research methodologies and disciplinary perspectives. When sufficient cases have been entered into these data sets, with data collected and coded using the standardized techniques developed, ReefBase and RAMP indicators will enable multivariate, quantitative analysis. Independent variables can be related to important dependent variables such as reef condition or management institution status to determine the amount of variance connected to the independent variables. Results of these analyses could provide decision makers with information that can be used to select alternative courses of action which will be based on more that the currently available unsystematic, anecdotal information (Pollnac, 1997). Relating RAMP indicators to coral reef ecosystem integrity will require the development of special indices and calibration.

3.5 DOES SUFFICIENT INFORMATION EXIST TO DRAFT BIOCRITERIA GUIDANCE

While not exhaustive, the above list of proposed coral reef bioindicators covers a wide range of taxonomic groups and monitoring techniques. With a few notable exceptions (Table 3.4), the majority of these proposed bioassays have not yet been fully developed into useable monitoring protocols.

In these respects, coral reef bioindicators lag far behind freshwater and temperate marine biomonitoring programs, many of which have undergone extensive calibration and have been developed into multi-metric indices of "biotic integrity" with well-defined interpretative frameworks (e.g., Karr *et al.* 1986, Lenat 1988, Lang *et al.* 1989, Karr 1991, Rosenberg and Resh 1993, Kerans and Karr 1994, Wilson and Jeffrey 1994). Many of these indices result in the calculation of a simple numerical "score" for a particular site, which can then be compared over time or with other sites. Such rankings have an intuitive appeal to resource managers and users, and can be an effective means of galvanizing political willpower towards pollution prevention and conservation activities.

Table 3.6: Existing usable coral reef ecosystem related bioindices.

Index	Pollutant	Parameters	Status	Reference	Location
Calibrated Numerical Coelobite Index	Drilling discharges	Points assigned for presence/ absence & abundance	Potential for monitoring sedimentation on coral is untested	Choi, 1982	Pacific - Philippines

Gastropod Imposex - RPS Index	Tributyltin	Frequency of imposex in females and relative penis size	Fully developed	Ellis and Pattisina, 1990	Caribbean, Pacific, Indian
Sessile Reef Diversity Index	Environmental conditions	Comparison of Shannon-Weaver heterogeneity index (H') & Pielou's evenness index (J')	Reported in Cuban journal and details un-available - but worth further investigation	Alcolado *et al*, 1994	Caribbean - Cuba
Nitrogen Isotope Ratios in Reef Organismal Tissues	Human (faecal) sewage d ^{15}N ratio of $^{15}N/^{14}N$	Fully calibrated for Indonesian coral reefs; further comparative work needed to test applicability to other geographic regions.	Risk *et al.*, 1994 Dunn, 1995 Risk & Erdmann, in press	Indonesia (Zanzibar, Maldives)	

3.5.1 Potential Reference Sites For U.S. Coral Reef Ecosystem Biocriteria Program

The availability of reference sites and associated data bases are also requirements for a U.S. Coral Reef Ecosystem Biocriteria Program. Table 3.7 lists some minimally impaired coral reef ecosystems that potentially could serve as biocriteria reference sites.

Table 3.7: Sites under United States jurisdiction with minimally impaired coral reef ecosystems (Jameson *et al.* 1995b) that warrant further investigation as reference sites.

Site	Caribbean / Western Atlantic	Gulf of Mexico	Pacific
Dry Tortugas National Park	X		
Flower Gardens National Marine Sanctuary		X	
Northwest Hawaiian Islands (uninhabited)			X
Wake Island			X
Mariana Islands (less Guam & Saipan)			X
Palmyra Atoll			X
Kingman Reef			X
Howland Island			X
Baker Island			X
Jarvis Island			X
Fagatele Bay National Marine Sanctuary			X

The following coral reef ecosystems at risk within United States jurisdiction (Jameson et al. 1995b) warrant further investigation as they may have localized, minimally impaired areas that could be used as reference sites (Table 3.8).

Table 3.8: Coral reef ecosystems at risk within United States jurisdiction that warrant further investigation as reference sites.

Coral Reef Ecosystems At Risk	Caribbean / Western Atlantic	Gulf of Mexico	Pacific
Florida reef tract (less The Dry Tortugas)	X		
Puerto Rico	X		
United States Virgin Islands	X		
Main Hawaiian Islands (inhabited)			X
Johnston Atoll			X
Mariana Islands - Guam			X

Mariana Islands - Saipan			**X**
American Samoa			**X**

3.5.2 Conclusion

At this time, sufficient information does not exist to draft biocriteria guidance for coral reef ecosystems. However, the research progress to date, as outlined above, provides a good spring board for developing a U.S. Coral Reef Ecosystem Biocriteria Program.

CHAPTER 4
What Research And/Or Projects Are Needed To Support Development of Biological Criteria Guidance For Coral Reef Ecosystem Assessment

Coral reefs offer several distinct advantages as sites for bioassessment and biocriteria programs. They are discrete systems that occur within a narrow range of biological and physical parameters and exhibit comparable habitats over a wide geographical range. However, as shown in Chapter 3, comprehensive taxonomic surveys and inventories on which biocriteria programs are ultimately based are inadequate. Other constraints include the lack of active field systematists and adequate laboratory facilities in many U.S. possessions. Without substantial long-term commitments of facilities and personnel in tropical U.S. States and Possessions (particularly in the Pacific), these problems will continue to restrict progress in implementing biological assessment and biocriteria programs in coral reef areas.

The following recommendations for next steps to support development of biological criteria for coral reef ecosystem assessment are tasks that can be accomplished in the next 5 years. They complement the framework outlined in: Draft Estuarine & Coastal Marine Waters Bioassessment & Biocriteria Technical Guidance (Gibson *et al.* 1997).

4.1 RECOMMENDATION: Develop A Program Action Plan To Implement The U.S. Coral Reef Ecosystem Biocriteria Program

A Program Action Plan for the U.S. Coral Reef Ecosystem Biocriteria Program should be produced that clearly defines goals, objectives, budgets, responsible parties and timetables for accomplishing this important program. The economic and social consequences for not acting quickly are clear and serious (Jameson *et al.* 1995a).

4.2 RECOMMENDATION: Draft A U.S. Coral Reef Ecosystem Biocriteria Research Strategy And Disseminate It On The Internet

As discussed in Chapter 3, coral reef research relevant to biocriteria development lags far behind freshwater and estuarine results. A biocriteria research strategy needs to be developed and supported to provide the basic indicators and indices for the coral reef ecosystem biocriteria program. In designing the strategy, acceptable levels of uncertainty for decisions made on the basis of potential biocriteria should be considered and data quality objectives should be established. The final coral reef ecosystem biocriteria research strategy should be widely disseminated to the research community so interested scientists will have a clear framework to guide future research programs.

The present study can provide the basis for a small working group to draft the research strategy for peer review and EPA approval.

A web site for the U.S. Coral Reef Ecosystem Biocriteria Program should be developed (or tied into existing coral related web sites) to disseminate information on the program.

4.2.1 Build Upon Promising Areas Of Bioindicator Research In The Research Strategy

The review of current and proposed reef bioindicators in Chapter 3 and Appendices 1-5 reveals a number of highly promising bioassays of water quality surrounding coral reefs. Further development of each of these biomonitoring protocols should not proceed in isolation; rather, the combination of a number of the bioindicator taxa into a multimetric coral reef index of integrity would be highly desirable and undoubtably more sensitive to a wider range of environmental perturbations than single-taxa bioassays. As suggested above, such indices should include at least some direct measures of the condition of hard coral assemblages, but should also include a variety of other taxa to ensure a taxonomically-comprehensive picture of current reef conditions.

Specific research and development needs for the majority of these bioassays include direct calibration of the indicator response to the environmental stress(es) it purports to monitor, comparative work in other geographic regions to test the widespread applicability of the assay, and development of an interpretative framework (preferably statistics-based) to allow standardized interpretation of biomonitoring results (e.g., a change in parameter **x** of **y** magnitude indicates an impact by **a, b** and/or **c** stressors and has **z** implications for reef biointegrity).

In some areas, basic faunal/floral inventories need to be conducted to identify tentative candidates for use as bioindicators before responses to various pollutants, toxicants, and other factors such as salinity, pH, dissolved oxygen, and temperature can be documented.

4.2.2 Conduct A Specially Designed Workshop To Suggest Potential New Bioindicators

A small, specially designed workshop should be conducted to include coral reef researchers, as well as researchers who have developed freshwater and estuarine bioindices, in order to get other perspectives on potential new bioindicators and the development of coral reef ecosystem biocriteria. This workshop would be designed in a way that would prepare participants in advance of the group meeting to address critical specific questions in their areas of expertise and important general questions relevant to the overall coral reef ecosystem biocriteria program.

4.2.3 Coordinate With Other Government Agencies To Fund The Research Strategy

EPA should work with other relevant government agencies, such as NOAA and NSF, to offer grants to accomplish the goals and objectives of the research strategy.

4.2.4 Select Coral Reef Ecosystem Bioindicators For The Research Strategy Using The Following Guidelines

Monitoring and assessment programs typically do not have the resources to measure all ecological attributes of concern to the public and to managers, and assessment tools must be cost-effective. Ideally, metrics selected for monitoring should be scientifically valid; should not require large amounts of expensive equipment nor extensive taxonomic identification; and should be relatively rapid in the field. The selected variables must be:

- Related to Biological Integrity - In general, almost any biological measurement is related to biological integrity, but some are more clearly tied to the properties of biotic systems of concern to society (e.g., native species, fish production, diverse trophic structure) (Suter 1993).

- Responsive to Environmental Stresses - Biological measurements and the metrics developed from them must respond to environmental stress. Metrics that are not monotonic (i.e., they do not consistently exhibit low values in response to one end of a stressor continuum and high values in response to the opposite end), or that respond oppositely to different stresses, are difficult to interpret in practice.

- Measurable with Low Error - Variability and measurement error should be controllable so that a reasonable sampling effort yields sufficient precision. Index period sampling (i.e., sampling during specific time periods in the annual cycle) is one way to reduce seasonal variability. However, there are costs in terms of information derived which may be prohibitive.

- Cost-effective - Cost of a metric should be proportional to the value of the information obtained. Usually, the simplest approach is most cost-effective and should be selected so long as results are sufficient to the agency's objectives.

- Environmentally Benign to Measure - Sampling methods that significantly disturb or alter habitats and biota should be avoided.

See section 3.4 for more discussion on bioindicator selection.

4.2.5 Develop A Multimetric Approach For Coral Reef Ecosystem Survey Protocols

The recommended approach to employ in developing coral reef ecosystem survey protocols is to define an array of metrics or measures that individually provide limited information on biological status, but when integrated, function as an overall indicator of biological condition. This is generally referred to as a multimetric approach.

The best-documented responses to environmental stressors according to Gray (1989) are:

- reduction in species richness;

- change in species composition to dominance by opportunistic and tolerant species and;

- reduction in mean size of organisms.

However, because responses may vary under different stresses, it is desirable to incorporate many attributes into the assessment process (Gray 1989). The principal strength of the multimetric approach is its ability to integrate information from individual, population, community, and ecosystem levels to allow evaluation as a single, ecologically-based index of water resource quality (Karr 1991, Karr and Kerans 1992, Karr *et al.* 1986, Plafkin *et al.* 1989).

A metric is a calculated term or enumeration representing some aspect of biological assemblage structure, function, or other measurable characteristic. Similarly, each of the assemblages (e.g., fish, benthic macroinvertebrates) measured would be expected to have a response range to perturbation events or degraded conditions. Thus, biosurveys targeting multiple species and assemblages (i.e., multimetric) will likely provide detection capability over a broad range of impacts, and the biocriteria derived from their results could provide protection to a large segment of the ecosystem.

The multimetric approach is the best developed and most extensively used method to date. The multimetric concept came to fruition with the fish Index of Biotic Integrity (IBI) first conceived by Karr (1981). The IBI aggregates various elements and surrogate measures of process into a single assessment of biological condition. Karr (1981) and Karr *et al.* (1986) demonstrated that combinations of these attributes or metrics provide valuable synthetic assessments of the status of water resources. Wilson and Jeffrey (1994) review benthic biological pollution indices in estuaries. Time and experience will ultimately determine the best approach or combination for each state to use in coral reef ecosystem assessment.

Metrics can be expressed numerically as integers or ratios. Consistent routines in normalizing individual metric values provide a means of combining metric scores which initially consisted of dissimilar numerical expressions. However, final decisions on impact/no impact or management actions are not made on the single, aggregated value alone. Rather, if comparisons to established reference values indicate an impairment in biological condition, component parameters (or metrics) are examined for their individual effects on the aggregated value and for indications of potential causes.

Assessment of biological integrity using this multimetric approach typically focuses on four broad classes of community properties. Ecological systems respond to anthropogenic impacts with changes in one or more of these classes of properties (e.g., Karr *et al.* 1986, Schindler 1988, Plafkin *et al.* 1989, Schindler *et al.* 1989, Karr 1991, Barbour *et al.* 1992). The four properties are:

- **Health of populations**, typically expressed as number of individuals per ml or as biomass, reflecting possible stress from anthropogenic sources.

- **Community structure and composition**, or the number and kinds of species in an assemblage. Exotic species are typically undesirable, and high diversity is typically desirable. Species structure metrics can include diversity and evenness indexes as well as presence of indicator species, counts of tolerant or intolerant species, and the percentage of individual taxa in comparison to the total number sampled.

- **Trophic structure**, or the relative proportion of different trophic levels and functional feeding groups (e.g., Barbour *et al.* 1992). In estuaries, abundant, diverse, and relatively large top carnivores (e.g., piscivorous fish) are typically desirable as representative of a broad, stable, and substantial trophic network.

- **System function**, or the productivity and material cycling of the system or its components (trophic levels, assemblages, species). Measures of system function can include primary production, standing stock biomass, or abundance proportions of taxonomic groups (e.g., crustaceans, mollusks, polychaetes), or comparisons of infauna vs. epifauna. Too many or too few organisms, compared to reference systems, indicates low biological integrity.

Since biological integrity is defined as an indicator of undisturbed conditions, it too must be measured relative to those conditions. The requirement of the biological criteria process for a reference by which to measure biological integrity makes it a practical tool (*sensu* Peters 1991) for managing society's impact on the natural environment.

4.2.6 Use Multivariate Analysis To Refine Bioindicators

A complementary approach for biological criteria development is multivariate analysis of biological and physical data from reference sites. Many types of multivariate analyses are used by ecologists; ordination and discriminant analysis have proved most useful for the purposes of bioassessment. The purpose of ordination analysis is to reduce the complexity of many variables (for example, abundance of 100 species from multiple estuarine site classes) into fewer variables, such that the sites and the species are ordered on the new variables. This provides a rational reduction to the most consistent indicators for use in biocriteria.

Discriminant analysis is also used in biocriteria development to determine which variables discriminate between two or more *a priori* defined groups (e.g., presumed reference and impaired sites). Variables that accurately discriminate between groups are useful predictors for sites whose resource condition is not presumed *a priori*. These variables serve the same function in criteria development as metrics.

4.3 RECOMMENDATION: Establish Interagency Cooperation

The U.S. Coral Reef Ecosystem Biocriteria Program could benefit in many ways by establishing strong relationships with the following programs.

4.3.1 EPA - Environmental Monitoring and Assessment Program (EMAP)

The EPA - EMAP program worked with NOAA in conducting status and trends monitoring in the Florida Keys in the early 1990's. However, EMAP does not now have a coral reef component. The U.S. Coral Reef Ecosystem Biocriteria Program should work to establish monitoring programs with EMAP.

Other EMAP programs that could assist the U.S. Coral Reef Ecosystem Biocriteria Program include the following.

Ecological Indicator Development Program - presently does not have a coral reef component.

Demonstration of Intensive Sites Project (DISPRO) Index Sites Program - uses National Park sites for Term environmental monitoring and presently does not have a coral reef component. The Dry Tortugas National Park or the Virgin Islands National Park would be potential candidates for future DISPRO coral reef ecosystem sites.

4.3.2 EPA - Ecological Risk Assessment

While not an actual program, the EPA Risk Assessment Forum has issued guidelines (USEPA 1998) for ecological risk assessment that describe the framework for evaluating scientific information to determine the adverse effects of physical and chemical stressors on the environment. The U.S. Coral Reef Ecosystem Biocriteria Program should be valuable to complement and strengthen existing EPA ecological risk assessment guidelines in the area of coral reef ecosystem assessment.

4.3.3 NOAA - National Marine Sanctuaries Program

The U.S. Coral Reef Ecosystem Biocriteria Program should cooperate with the National Marine Sanctuaries Program in the:

- Designation of reference sites;
- Use of monitoring personnel;
- Data management; and
- Field logistical support.

4.3.4 NOAA - Special Projects Office - Coastal Assessment & Data Synthesis (CADS)

Framework Team

Dr. Steve Rohmann (301-713-3000 x 137) of the CADS Framework Team has been working on coral reef benthic habitat classification for the Florida Keys National Marine Sanctuary since 1992 (Clarke and Rohmann 1994). They are producing a Benthic Habitats of the Florida Keys CD in May 1998 that will include the digital data for the habitat maps and a data publisher for creating habitat maps. The U.S. Coral Reef Ecosystem Biocriteria Program should make this office a "first stop" in their classification efforts and benefit from the experience in coral reef habitat classification gained by this NOAA office.

4.3.5 National Park Service

The U.S. Coral Reef Ecosystem Biocriteria Program should make special efforts to work closely with the Dry Tortugas National Park and Virgin Islands National Park. Both of these Parks can provide:

- Long-term monitoring data;
- Experienced personnel; and
- Can assist in the selection of reference sites.

4.3.6 CARICOMP - Puerto Rico And Florida Keys

The CARICOMP Program can also provide the U.S. Coral Reef Ecosystem Biocriteria Program with:

- Monitoring data;
- Experienced personnel; and
- Assistance in selecting reference sites.

4.3.7 Florida Center For Public Management

The Florida Coastal Management Program - Florida Department of Community Affairs, contracted with the Florida Center for Public Management to produce the FACT'97 and Florida Environmental Index Series. Aspects of both of these documents have the potential to be used in other coral reef areas outside of Florida.

4.4 RECOMMENDATION: Begin Preliminary Coral Reef Habitat Classification

Designing an appropriate habitat classification system for coral reef ecosystems under U.S. jurisdiction will, to some degree, depend on the type of bioindicators used for the U.S. Coral Reef Ecosystem Biocriteria Program. Ideally, the types of bioindicators used in the biocriteria program will allow for a very simplified habitat classification system (e.g., one that will not depend on a certain species or assemblage of coral to be present or require a certain geomorphological shape of the reef, etc.). A well designed biocriteria program and associated classification system will broaden the number of coral reef ecosystems that potentially can be used as reference sites. As research progresses, the types of bioindicators and indices to be used in the program will become clearer and this will allow for the development of the classification system.

NOAA's Special Projects Office - Coastal Assessment & Data Synthesis (CADS) Framework Team, who conducted coral reef habitat classification work as part of the Florida Keys National Marine Sanctuary resource mapping program, can potentially provide valuable experience in this endeavor.

4.5 RECOMMENDATION: Begin Selecting Reference Sites And Developing Associated Data Bases

The process of evaluating and selecting reference sites can begin immediately. Selecting unimpaired reference sites in the Pacific will be easier than in the Western Atlantic and Caribbean, where population centers have impacted many coral reef ecosystems (Jameson *et al.* 1995).

Because absolutely pristine coral reef ecosystem habitats probably do not exist, resource managers must decide on acceptable levels of minimum impacts that exist or that are achievable in a given region. Acceptable reference conditions will differ among geographic regions and states because coral reef oceanographic conditions, gradients, trophic state, bottom sediment types, morphology and biological communities differ between regions.

Reference conditions can be established in a variety of ways but should include information derived from: historical data; reference sites; mathematical models; and consensus of expert opinion. It is important to recognize that the reference condition is best developed from a population of sites, not from a single site. However, in some instances, particularly coastal environments and sites influenced by controversial land uses, the use of site-specific nearfield/farfield stations may be necessary and appropriate to augment the reference condition.

- Historical Data - are usually available that describe biological conditions in the coastal marine region over some period of time in the past. Careful review and evaluation of these data provide insight about the communities that once existed and/or those that may be reestablished. Review of the literature and existing data is an important initial phase in the biocriteria development process. However, if data have not been collected for this specific purpose, they need to be carefully reviewed before being applied.

- Reference Sites - are minimally impaired locations in similar water bodies and habitat types at which data are collected for comparison with test sites. Reference sites could include: sites that are upstream of point sources; sites occurring along impact gradients (nearfield/farfield); and regional reference sites that may be applied to a variety of test sites in a given area.

- Mathematical Models - include mathematical models (logical constructs following from first principles and assumptions), statistical models (built from observed relationships between variables), or a combination of the two. The degree of complexity of mathematical models to predict reference conditions is potentially unlimited with attendant increased costs and loss of predictive ability as complexity increases (Peters 1991). However, models that predict biological reference conditions should only be used with great caution, because they are complex and often untestable hypotheses (Oreskes *et al.* 1994, Peters 1991).

- Expert Opinion/Consensus - A consensus of qualified experts is always needed for assessing all of the above information; establishing the reference condition; and helping develop the biocriteria. This is especially the case in impaired locales where no candidate reference sites are acceptable and models are deemed unreliable. In these cases, expert consensus is a workable alternative used to establish reference "expectations". Under such circumstances, the reference condition may be defined using a consensus of expert opinion based on sound ecological principles applicable to a region of interest. The procedures for these determinations and decisions should be well documented for the record.

Work should begin as soon as possible to compile all existing data on selected reference sites and organize the data into relational data bases.

4.5.1 Evaluate The Usefulness Of Appropriate Past Short-Term Monitoring Data

Many short-term or project specific monitoring efforts have been conducted, but repeating these is, in many cases, dependent on the cooperation of the personnel who conducted the original work. Data from these short-term monitoring efforts (less than 5 years in duration) could be useful building blocks for a U.S. biocriteria program and the potential of each of these efforts should be evaluated.

4.5.2 Designate Reference Sites As National Marine Sanctuaries

To ensure the long-term protection of reference sites special efforts should be made to work with NOAA to make the designation of reference sites as "research" national marine sanctuaries a top priority.

4.6 RECOMMENDATION: Develop U.S. Coral Reef Ecosystem Biocriteria Program Taxonomic Infrastructure

The following steps can be taken to insure that taxonomic necessities are addressed adequately in the U.S. Coral Reef Ecosystem Biocriteria Program.

- A complete taxonomic study and database for bioindicators used in the program should be maintained by taxonomically competent personnel.
- Nontechnical bioindicator identification guides should be prepared and updated as needed.
- A centralized collection of all bioindicator species should be maintained and curated for reference and research purposes.
- Competent taxonomic personnel should be provided by agencies involved in the U.S. Coral Reef Ecosystem Biocriteria Program.
- Develop agreements with relevant agencies to share data and information.

4.7 RECOMMENDATION: Initiate And Support National And International Watershed Management Programs.

The importance of healthy watersheds (and airsheds) to coral reef ecosystems can not be overstated. There are countless examples of declining fish and invertebrate species diversity and abundance in American rivers over the last century (Karr and Kerans 1991). If upstream biota are struggling for existence, it is not surprising that downstream residents (coral reef ecosystems) are hanging on for dear life.

In the U.S., it is encouraging to see the hundreds of local watershed management organizations (NGOs) being formed across the land to address clean water challenges. Over time, these local efforts to enforce total maximum daily load (TMDL) requirements for nutrients, sediments and bacteria, set by the federal government, will make a positive difference to estuarine and marine environments (i.e., coral reef ecosystems). It is also encouraging to see state governments across the U.S. also starting to initiate freshwater and estuarine biocriteria programs. International efforts by U.S. government agencies and NGOs should be made to help establish similar biocriteria and watershed management programs in countries with potential downstream impacts on U.S. coral reef ecosystems (see 2.1 Florida reef tract example). Without effective local upstream efforts on the national and international fronts a downstream US. Coral Reef Ecosystem Biocriteria Program will be, in the end, frustrated and ineffective.

REFERENCES

Alcolado PM, Herrera-Mareno A, Martinez-Estalella N (1994) Sessile communities as environmental biomonitors in Cuban coral reefs. In: Ginsburg RN (ed) Proceedings of the Colloquium on Global Aspects of Coral Reefs, University of Miami, pp 27-33

Alve E (1995) Benthic foraminiferal responses to estuarine pollution: a review. J Foram Res 25:190-203

Aronson RB, Edmunds PJ, Precht WF, Swanson DW, Levitan DR (1994) Large-scale, long-term monitoring of Caribbean coral reefs: simple, quick, inexpensive techniques. Atoll Res Bull No. 421

Ashanullah M (1976) Acute toxicity of cadmium and zinc to seven invertebrate species from Western Port, Victoria. Aust J of Freshwater Res 27:187-196

Baker JM (1971) Growth stimulation following oil pollution. In: Cowell EB (ed) The ecological effects of oil on pollution and littoral communities, London Inst of Petroleum, pp 72-77

Barbour MT, Plafkin JL, Bradley BP, Graves CG, Wisseman RW (1992) Evaluation of EPA's rapid bioassessment benthic metrics: metric redundancy and Variability among-reference stream sites. Envir Toxicol and Chem 11:437-449

Barnard JL (1958) Amphipod crustaceans as fouling organisms in Los Angeles-Long Beach harbors, with reference to the influence of seawater turbidity. Calif Fish and Game 44:161-170

Barnes DJ (1983) Profiling coral reef productivity and calcification using pH and oxygen electrode techniques. J Exp Mar Biol Ecol 66:149-161

Bell JD, Galzin R (1984) Influence of live coral cover on coral reef fish communities. Mar Ecol Prog Ser 15:265-274

Bergquist Jr. GT, Emmert NO, Silvestri JA, Parker D, Plagens M, Souza P, Wilson J (1997) Florida assessment of coastal trends FACT. Florida Coastal Management Program, Florida Department of Community Affairs

Bernard JL (1961) Relationship of California amphipod faunas in Newport Bay and in the open sea. Pacific Naturalist 2:166-186

Barnes DJ (1983) Profiling coral reef productivity and calcification using pH and oxygen electrode techniques. J Exp Mar Biol Ecol 66:149-161

Bell JD, Galzin R (1984) Influence of live coral cover on coral reef fish communities. Mar Ecol Prog Ser 15:265-274

Bergquist Jr. GT, Emmert NO, Silvestri JA, Parker D, Plagens M, Souza P, Wilson J(1997) Florida assessment of coastal trends FACT. Florida Coastal Management Program, Florida Department of Community Affairs

Bernard JL (1961) Relationship of California amphipod faunas in Newport Bay and in the open sea. Pacific Naturalist 2:166-186

Birkeland C (1987) Nutrient availability as a major determinant of differences among coastal hard-substratum communities in different regions of the tropics. In: Birkeland C (ed) Differences between Atlantic and Pacific tropical marine Coastal systems: community structure, ecological processes, and productivity. UNESCO, Paris, pp 45-90

Bilyard GR (1987) The value of benthic infauna in marine pollution monitoring studies. Mar Poll Bull 18:581-585

Birkeland C, Lucas JS (1990) Acanthaster planci: major management problem of coral reefs. CRC Press, Florida

Bouchon-Navaro Y,Bouchon C, Harmelin-Vivien ML (1985) Impact of coral degradation on a chaetodontid fish assemblage. Proc 5th Int Coral Reef Symp 5:427-432

Brown BE (ed)(1986) Human induced damage to coral reefs. UNESCO Reports in Marine Science, No. 40, Jakarta

Brown BE (1988) Assessing environmental impacts on coral reefs. Proc 6th Int Coral Reef Symp 1:71-80

Brown BE, Holly MC (1982) Metal levels associated with tin dredging and smelting and their effect upon intertidal reef flats at Ko Phuket, Thailand. Coral Reefs 1:131-137

Brown BE, Howard LS (1985) Assessing the effects of "stress" on reef corals. Adv Mar Biol 22:1-63

Brown BE, Le Tissier MD, Scoffin TP,Tudhope AW (1990) Evaluation of the environmental impact of dredging on intertidal coral reefs at Ko Phuket, Thailand, using ecological and physiological parameters. Mar Ecol Prog Ser 65:273-281

Bryan GW, Hummerstone LG (1973) Brown seaweed as an indicator of heavy metals in estuaries in South-West England. J Mar Biol Assoc UK 53:705-720 Burke L, Bryant D, McManus J, Spalding M (1998) Reefs at risk: a mapped based indicator of potential threats to the worlds coral reefs. World Resources Institute, Washington DC

Cairns J (1986) The myth of the most sensitive species. Bioscience 36:670-672

Cairns J, Pratt JR (1989) The scientific basis of bioassays. Hydrobiologia 188/189:5-20

Chadwick-Furman NE (1996) Effects of scuba diving on coral reef invertebrates in the U.S. Virgin Islands: implications for the management of diving tourism. Proc 6th Int Coelenterate Bio Conf, Amsterdam 1996

Chalker B, Carr K , Gill E (1985) Measurement of primary production and calcification in sites on coral reefs using electrode techniques. Proc 5th Int Coral Reef Congress 6:167-172

Choi DR (1982) Coelobites as indicators of environmental effects caused by offshore drilling. Bull Mar Sci 32:880-889

Clark AE, Rohmann SO (1994) Mapping and analyzing benthic habitats in the Florida Keys National Marine Sanctuary. Proc Second Thematic Conf on Remote Sensing from Marine and Coastal Environments, New Orleans, LA

Clarke KR (1993) Non-parametric multivariate analyses of change in community structure. Aust J Ecol 18:117-143

Clarke KR, Warwick RM, Brown BE (1993) An index showing breakdown of seriation, related to disturbance, in a coral reef assemblage. Mar Ecol Prog Ser 102:153-160

Cockey E, Hallock P, Lidz BH (1996) Decadal-scale changes in benthic foraminiferal assemblages off Key Largo, Florida. Coral Reefs 15(4): 237-248

Cortes J, Risk MJ (1985) A reef under siltation stress: Cahuita, Costa Rica. Bull Mar Sci 36:339-356

Costanza, R.,Funtowicz SO, and Ravetz JR (1992) Assessing and communicating data quality in policy-relevant research. Environ. Manage. 16(l):121-131

Cranston PS (1990) Biomonitoring and invertebrate taxonomy. Environmental Monitoring and Assessment 14:265-273

Crosby MP, Reese ES (1996) A manual for monitoring coral reefs with indicator species: butterflyfishes as indicators of change on Indo-Pacific Reefs. NOAA, Silver Spring Maryland

Crosby MP, Gibson GR, and Potts KW (eds) (1996) A coral reef symposium on practical, reliable, low cost monitoring methods for assessing the biota and habitat conditions of coral reefs, January 26-27, 1995. Office of Ocean and Coastal Resource Management, National Oceanic and Atmospheric Administration, Silver Spring, MD

Dahl AL (1981) Monitoring coral reefs for urban impact. Bull Mar Sci 31:544-551

Dahl AL, Lamberts AE (1977) Environmental impact on a Samoan coral reef: a resurvey of Mayor's 1917 transect. Pac Sci 31(3):309-319

de Kock WC, Kramer KJ (1994) Active biomonitoring by translocation of bivalve molluscs. In: Kramer KJ (ed) Biomonitoring of coastal waters and estuaries, CRC Press, Boca Raton pp. 51-84

DeVantier LM (1986) Studies in the assessment of coral reef ecosystems. In: Brown BE (ed) Human induced damage to coral reefs, UNESCO Reports in Marine Science, 40:99-111

Dixon JA, Fallon Scura L, van't Hof T (1993) Meeting ecological and economic goals: marine parks in the Caribbean. Ambio 22:117-125

Dodge RE, Jickells TD, Knap AH, Boyd S, Bak RPM (1984) Reef-building coral skeletons as chemical pollution (phosphorus) indicators. Mar Poll Bull 15:178-187

Dodge RE, Logan A, Antonius A (1982) Quantitative reef assessment studies in Bermuda: a comparison of methods and preliminary results. Bull Mar Sci 32: 745-760

Doherty PJ (1991) Spatial and temporal patterns in recruitment. In: Sale OF (ed) Ecology of fishes on coral reefs. Academic Press, San Diego, pp 261-293

Done TJ (1995) Ecological criteria for evaluating coral reefs and their implications for managers and researchers. Coral Reefs 14:183-192

Dunn JJ (1995) Application of Nitrogen isotopes and other tracers of anthropogenic input to modern reefs. Unpublished MSc thesis, McMaster Univ

Dustan P (1994) Developing methods for assessing coral reef vitality: a tale of two scales. In: Ginsburg RN (ed) Proceedings of the Colloquium on global aspects of coral reefs: health, hazards and history, Univ Miami, pp 38-45

Dustan P, Halas JC (1987) Changes in the reef-coral community of Carysfort Reef, Key Largo, Florida: 1974-1982. Coral Reefs 6:91-106

Eakin CM, McManus JW, Spalding MD, Jameson SC (1997) Coral reef status around the world: where are we and where do we go from here? Proc 8th Int Coral Reef Symp 1:277-282. Internet website address: http://www.ogp.noaa.gov/misc/coral/8icrs EXIT disclaimer

Edinger EN (1991) Mass extinction of Caribbean corals at the Oligocene-Miocene boundary: paleoecology, paleooceanography, paleobiogeography. Unpub MSc Thesis, Geology, McMaster Univ

Ellis DV, Pattisina LA (1990) Widespread neogastropod imposex: a biological indicator of global TBT contamination? Mar Poll Bull 21:248-253

English S, Wilkinson C, Baker V (eds) (1994) Survey Manual for Tropical Marine Resources. Australian Institute of Marine Science, Townsville, Australia

Erdmann MV (1997a) Butterflyfish as bioindicators - a review. Reef Encounter 21:7-9

Erdmann MV (1997b) The ecology, distribution and bioindicator potential of Indonesian coral reef stomatopod communities. PhD dissertation, Univ. California Berkeley

Erdmann MV, Caldwell RL (1997). Stomatopod crustaceans as bioindicators of marine pollution stress on coral reefs. Proc 8th International Coral Reef Symposium 2:1521-1526

Erdmann MV, Sisovann O (in press) Abundance and distribution of reef-flat stomatopods in Teluk Jakarta and Kepulauan Seribu. In: UNESCO Reports in Marine Science, Proceedings of the UNESCO Coral Reef Evaluation Workshop, Jakarta, Indonesia, 1995

Esch GW, Gibbons JW, Bourque JE (1975) An analysis of the relationship between stress and parasitism. Am Midland Nat 93:339-353

Evans SM, Dawson M, Day J, Frid CL, Gill ME, Pattisina LA, Porter J (1995) Domestic waste and TBT pollution in coastal areas of Ambon. Mar Poll Bull 30:109-115

Faith DP (1990) Benthic macroinvertebrates in biological surveillance: Monte Carlo significance tests on functional groups' responses to environmental gradients. Environmental Monitoring and Assessment 14:247-264

Foale S (1993) An evaluation of the potential of gastropod imposex as a bioindicator of tributyltin pollution in Port Phillip Bay, Victoria. Mar Poll Bull 26:546-552

Gajbhiye SN, Vhayalakshmi RN, Desai BN (1987) Toxic effects of domestic sewage on zooplankton. Mahasagar-Bull Nat Inst Mar Ocean 20:129-133

Garrity SD, Levings SC (1990) Effects of an oil spill on the gastropods of a tropical intertidal reef flat. Mar Env Res 30:119-153

Gates R, Brown BE (1985) The loss of zooxanthellae in the sea anemone Anemonia viridis (Forsskal) under stress. Proc 5th Int Coral Reef Congress 2:143

Gibbs PE, Bryan GW (1994) Biomonitoring of tributyltin (TBT) pollution using the imposex response of neogastropod molluscs. In: Kramer KJ (ed) Biomonitoring of coastal waters and estuaries, CRC Press, Boca Raton pp 205-226

Gibson GR, Barbour MT, Stribling JB, Gerritsen J, Karr JR (1996) Biological Criteria and Technical Guidance for Streams and Small Rivers. EPA 822-B-96-001. USEPA, Office of Science and Technology, Health and Ecological Criteria Division, Washington, DC

Gibson GR, Bowman ML , Snyder BD, Gerritsen J (1997). Draft estuarine and coastal waters bioassessment and biocriteria technical guidance. USEPA, Office of Science and Technology, Health and Ecological Criteria Division, Washington, DC

Ginsburg RN, Bak RP, Kiene WE, Gischler E, Kosmynin V (1996) Rapid assessment of reef condition using coral vitality. Reef Encounter 19:12-14

Ginsburg RN compiler (1994) Proceedings of the colloquium on global aspects of coral reefs: health, hazards and history, 1993. Rosenstiel School of Marine And Atmospheric Science, University of Miami

Goldberg ED, Bowen VT, Farrington JW, Harvey J, Martin JH, Parker PL, Riseborough RW, Robertson W, Schneider E, Gamble E (1978) The Mussel Watch. Environ Cons 5:101-125

Gomez ED, Yap HT (1988) Monitoring reef conditions. In: Kenchington RA, Hudson BT (eds) Coral Reef Management Handbook, UNESCO/ROSTSEA, Jakarta, pp 187-195

Gomez ED, Alino PM, Yap HT, Licuanan WY (1994) A review of the status of Phillipine reefs. Mar Poll Bull 29:62-68

Gray JS (1981) Detecting pollution induced changes in communities using the log-normal distribution of individuals among species. Mar Poll Bull 12:173-176

Gray JS (1989) Effects of environmental stress on species rich assemblages. Biol J Linnean Soc 37:19-32

Gray JS, Mirza FB (1979) A possible method for the detection of pollution-induced disturbance on marine benthic communities. Mar Poll Bull 10: 142-146

Green RH, Vascotto GL (1978) A method for the analysis of environmental factors controlling patterns of species composition in aquatic communities. Water Res 12:583-590

Grigg RW (1997) Hawaii's coral reefs: status and health in 1997, the International Year of the Reef. In: Grigg RW and Birkeland C (eds) Status of Coral Reefs In the Pacific, Sea Grant College Program, School of Ocean and Earth Science and Technology, University of Hawaii

Grigg RW, Dollar SJ (1990) Natural and anthropogenic disturbance on coral reefs. In: Dubinsky Z (ed) Ecosystems of the World, 25:439-452

Hallock P (1988) The role of nutrient availability in bioerosion: consequences to carbonate buildups. Palaeogeog Palaeoclimatol Palaeoecol 63:275-291

Hallock P, Schlager W (1986) Nutrient excess and the demise of coral reefs and carbonate platforms. Palaios 1:389-398

Hallock P, Muller-Karger FE, Halas JC (1993a). Coral reef decline. Res Explor 9:358-378

Hanna RG, Muir GL (1990) Red Sea corals as biomonitors of trace metal pollution. Env Mon Asses 14:211-222

Harger JRE (1995) Coral reefs-uses and assessment for sustainable development. UNESCO-IOC report. Paris

Hart BH, Fuller SLH (1979) Pollution ecology of estuarine invertebrates. New York: Academic

Hawkins JP, Roberts CM (1996) Estimating the carrying capacities of coral reefs for scuba diving. Proc 8th Int Coral Reef Sym 2:1923-1926, Panama

Herrnkind WF, Butler MJ, Tankersley RA (1988) The effects of siltation on recruitment of spiny lobsters, Panulirus argus. Fish Bull U.S. 86: 331-338

Hirschfield HI, Charmatz R, Henson L (1968) Foraminifera in samples taken from Eniwetok Atoll in 1956. J Protozool 15:497-502

Hodgson G (1997) Reef Check core methods. Internet website address: http://www.reefcheck.org/ EXIT disclaimer

Holmes KE (1997) Eutrophication and its effect on bioeroding sponge communities. Proc 8th Int Coral Reef Symp 2:1411-1416

Hourigan TF, Tricas TC, Reese ES (1988) Coral reef fishes as indicators of environmental stress in coral reefs. In Soule DF, Kleppel GS (eds) Marine Organisms as Indicators. Springer-Verlag, New York, pp 107-135

Hudson JH (1981) Growth rates in Montastrea annularis: a record of environmental change in the Florida Keys. Proc 4th Int Coral Reef Symp 2:233-240

Hungspreugs M, Yuangthong C (1984) The present levels of heavy metals in some molluscs in the upper Gulf of Thailand. Water, Air and Soil Pollution 22:395-402

International Union for the Conservation of Nature (IUCN) (1993) Reefs at risk: A program for action. Rue Mauverney 28, CH-1196, Gland Switzerland

Jackson JB, Cubit JD, Keller BD, Batista V, Burns K, Caffey HM, Caldwell RL, Garrity SD, Getter CD, Gonzalez C, Guzman HM, Kaufman KW, Knap AH, Levings SC, Marshall MJ, Steger R, Thompson RC, Weil E (1989) Ecological effects of a major oil spill on Panamanian coastal marine communities. Science 243:37-44

Jameson SC, McManus JW, Spalding MD (1995a) State of the reefs: regional and global perspectives. International Coral Reef Initiative, US Department of State, Washington, DC. Internet website address: http://www.ogp.noaa.gov/misc/coral/sor/ EXIT disclaimer

Jameson SC, (1995b) Coral reef ecosystems. In: Laroe ET, Farris GS, Puckett CE,Doran PD, Mac MJ (eds) Our living resources - coastal and marine ecosystems, National Biological Service, US Dept. of the Interior, Washington, DC, pp 280-281

Jameson SC, Mansour HM, Riegl B (1997) Rapid ecological assessment of forty-eight diving sites in the Egyptian Red Sea Elba Protectorate: A historical perspective from 1987 - 1996. Winrock International (Arlington, VA) Environmentally Sustainable Tourism Project Report to USAID Egypt, Cairo

Jones GP, Kaly VL (1996) Criteria for selecting marine organisms in biomonitoring studies. In: Schmitt RJ, Osenberg CW (eds) Detecting ecological impacts: concepts and applications in coastal habitats. Academic Press, New York, pp 29-48

Jones RJ (1997) Zooxanthellae loss as a bioassay for assessing stress in corals. Mar Ecol Prog Ser 149:163-171

Karr JR (1991). Biological integrity: a long-neglected aspect of water resource management. Ecol Appl 1:66-84

Karr JR (1981) Assessment of biotic integrity using fish communities. Fisheries 6(6):21-27

Karr JR, Fausch KD, Angermeier PL, Yant PR, Schlosser IJ (1986) Assessing biological integrity in running waters: a method and its rationale. Illinois Natural History Survey, Special Publication 5

Karr JR and Kerans BL (1992) Components of biological integrity: Their definition and use in development of an invertebrate IBI. In: Davis WS and Simon TP (eds) Proceedings of the 1991 Midwest Pollution Control Biologists Meeting, Chicago. EPA-905/R-92/003, USEPA, Region V, Chicago, IL. Pp 1-16

Kerans BL, Karr JR (1994) A benthic index of biotic integrity (B-IBI) for rivers of the Tennessee Valley. Ecol Appl 4:768-785

Kimball KD, Levin SA (1985) Limitations of laboratory bioassays: the need for ecosystem-level testing. Bioscience 35:165-171

Kinsey DW (1988) Coral reef system response to some natural and anthropogenic stresses. Galaxea 7:113-128

Kovacs M (1992) Biological indicators in environmental protection. Akademiai Kiado, Budapest
Lang C, L'Eplattenier G, Reymond O (1989) Water quality in rivers of western Switzerland: Application of an adaptable index based on benthic invertebrates. Aq Sci 51:224-234

Lee WY, Welch MF, Nicol JAC (1977) Survival of two species of amphipods in aqueous extracts of petroleum oils. Mar Poll Bull 8:92-94

Lenat DR (1988) Water quality assessment of streams using a qualitative collection method for benthic macroinvertebrates. J N Amer Benthological Soc 7:222-233

Lenat DR, Smock LA, Penrose DL (1980) Use of benthic macroinvertebrates as indicators of environmental quality. In: Worf DL (ed) Biological monitoring for environmental effects, DC Heath and Co

Lidz L (1966) Planktonic foraminifera in the water column of the mainland shelf off Newport Beach, California. Limnol Oceanogr 11:257-263

Linden O (1976a) Effects of oil on the reproduction of the amphipod Gammarus oceanicus. Ambio 5:36-37

Linden O (1976b) Effects of oil on the amphipod Gammarus oceanicus. Envir Poll 10:239-250

Maher WA, Norris RH (1990) Water quality assessment programs in Australia: deciding what to measure and how and where to use bioindicators. Env Mon Assess 14:115-130

McLanahan TR (1997) Coral reef monitoring-the state of our art. Reef Encounter 20:9-11.

McLusky DS (1967) Some effects of salinity on the survival, moulting, and growth of Corophium volutator (amphipoda). J Mar Biol Assoc of the UK 47:607-617

McLusky DS (1970) Salinity preference in Corophium volutator. J Mar Biol Assoc of the UK 50:747-752

McManus JW, Ablan MC, Vergara SG, Menez LA, Reyes KP, Gorospe ML, Halmarick L (1997) Reefbase aquanaut survey manual. ICLARM Educational Series 18, Manila

McVikar AH, Bruno DW, Fraser CO (1988) Fish disease in the North Sea in relation to sewage sludge dumping. Mar Poll Bull 19:169-173

Meijering MPD (1991) Lack of oxygen and low pH as limiting factors for Gammarus in Hessian brooks and rivers. Hydrobiologia 223:159-161

Nash SU (1989) Reef diversity index survey method for nonspecialists. Trop Coast Area Mgmt 4:14-17

Noss RF (1990) Indicators for monitoring biodiversity: a hierarchical approach. Cons Biol 4:355-364

Oakden JM, Oliver JS, Flegal AR (1984) Behavioral responses of a phoxocephalid amphipod to organic enrichment and trace metals in sediment. Mar Ecol Prog Ser 14:253-257

Osenberg CW, Schmitt RJ, Holbrook SJ, Abu-Saba KE, Flegal AR (1994) Detection of environmental impacts: natural variability, effect size, and power analysis. Ecol Appl 4:16-30

Pearson DL (1994) Selecting indicator taxa for the quantitative assessment of biodiversity. Phil Trans R Soc Lond B 345:75-79

Pearson RG (1981) Recovery and recolonization of coral reefs. Mar Ecol Prog Ser 4:105-122

Pearson TH, Gray JS, Johannessen PJ (1983) Objective selection of sensitive species indicative of pollution-induced changes in benthic communities. 2. Data analyses. Mar Ecol Prog Ser 12:237-255

Pearson TH, Rosenberg R (1978) Macrobenthic succession in relation to organic enrichment and pollution of the marine environment. Oceanogr Mar Biol Ann Rev 16:229-311

Percy JA (1976) Responses of Arctic marine crustaceans to crude oil and oil-tainted food. Envir Poll 10:152-162

Peters EC, Gassman NJ, Firman JC, Richmond RH, Power EA (1997) Ecotoxicology of Tropical Marine Ecosystems. J of Env Tox and Chem 16:12-40

Peters, R.H. (1991) A Critique for Ecology. Cambridge University Press, Cambridge.

Peterson BJ, Fry B (1987) Stable isotopes in ecosystem studies. Ann Rev Ecol Syst 18:293-320

Phillips DJH (1980) Quantitative aquatic biological indicators. Applied Science Publishers, Ltd London

Phillips DJH (1994) Macrophytes as biomonitors of trace metals. In: Kramer KJ (ed) Biomonitoring of coastal waters and estuaries, CRC Press, Boca Raton pp. 85-106

Pielou EC (1966) The measurement of diversity in different types of biological collections. J Theor Biol 13:131-144

Plafkin JL, Barbour MT, Porter KD, Gross SK, Hughes RM (1989) Rapid bioassessment protocols for use in streams and rivers: benthic macroinvertebrates and fish, EPA/440/4-89-001, USEPA, Office of Water, Washington, DC

Podani J (1992) Monitoring system. In: Kovacs M (ed) Biological indicators in environmental protection. Ellis Horwood, UK pp 12-16

Pollnac RB (1997) Monitoring and evaluating coral reeef management. Intercoast Network 29: Fall 1997, Coastal Resources Center, Univ of Rhode Island

Reese ES (1981) Predation on corals by fishes of the family Chaetodontidae: implications for conservation and management of coral reef ecosystems. Bull Mar Sci 31:594-604

Reese ES (1994) Reef fishes as indicators of conditions on coral reefs. In: Ginsburg RN (ed) Proc of Colloquium on Global Aspects of Coral Reefs. Univ of Miami, pp 59-65

Richardson LL (1996) Monitoring and assessment of coral reef health: coral disease incidence and cyanobacterial blooms as reef health indicators. In: Crosby MP, Gibson GR, Potts KW (eds) A coral reef symposium on practical, reliable, low cost monitoring methods for assessing the biota and habitat conditions of coral reef, January 26-27, 1995. Office of Ocean and Coastal Resource Management, National Oceanic and Atmospheric Administration, Silver Spring, MD

Richmond RH (1993) Coral reefs: Present problems and future concern resulting from anthropogenic disturbance. American Zoologist 33:524-536

Richmond RH (1994a) Coral reef resources: Pollution's impacts. Forum for Applied Research and Public Policy, Oak Ridge Natl Lab 9:54-57

Richmond RH (1994b) Effects of coastal runoff on coral reproduction. In Ginsburg RN (ed) Proc of the Colloquium on Global Aspects of Coral Reefs. Univ. of Miami, pp 360-364

Richmond RH (1995) Hybridization as an evolutionary force in mass-spawning corals. J of Cellular Biochem 19B:341

Richmond RH (1996) Reproduction and recruitment in corals: critical links in the persistence of reefs. In: Birkeland CE(ed) Life and Death of Coral Reefs. Chapman and Hall, NY, pp 175-197

Riegl B, Velimirov B (1994) The structure of coral communities at Hurghada in the Red Sea. P.S.Z.N.I: Marine Ecology 15(3/4):213-231

Riegl B, Velimirov B (1991) How many damaged coral in Red Sea reef systems? A quantitative survey. Hydrobiologia 216/217:249-256

Risk MJ (1992) Musings on Monitoring. Reef Encounter 12: 7-9

Risk MJ, Dunn JJ, Allison WP, Horrill C (1994) Reef monitoring in Maldives and Zanzibar: Low-tech and high-tech science. In: Ginsburg RN (ed) Proc of Colloquium on Global Aspects of Coral Reefs. Univ of Miami, pp 66-72

Risk MJ, Erdmann MV (in press) Isotopic composition of Nitrogen in stomatopod tissues as an indicator of human sewage impacts on Indonesian coral reefs. Mar Poll Bull

Risk MJ, Sammarco PW, Edinger EN (1995) Bioerosion in Acropora across the continental shelf of the GBR. Coral Reefs 14:79-86

Roberts CM, Ormond RF (1987) Habitat complexity and coral reef fish diversity and abundance on Red Sea fringing reefs. Mar Ecol Prog Ser 41:1-8

Roberts CM, Ormond RF, Shepherd AR (1988) The usefulness of butterflyfishes as environmental indicators on coral reefs. Proc 6th Intl Coral Reef Symp 2:331-336

Rogers CS (1990) Responses of coral reefs and reef organisms to sedimentation. Mar Ecol Prog Ser 62:185-202

Root M (1990) Biological monitors of pollution. Bioscience 40:83-86

Rose CS, Risk MJ (1985) Increase in Cliona delitrix infestation of Montastrea cavernosa heads on an organically polluted portion of the Grand Caymans. Mar Ecol 6:345-363

Rosenberg DM, Resh VH (1993) Freshwater biomonitoring and benthic macroinvertebrates. Chapman and Hall, New York

Sammarco PW, Risk MJ (1990) Large-scale patterns in internal bioerosion of Porites: cross continental shelf trends on the Great Barrier Reef. Mar Ecol Prog Ser 59:145-156

Sandberg DM, Michael AD, Brown B, Beebe-Center R (1972) Toxic effects of fuel oil on haustoriid amphipods and pagurid crabs. Bio Bull 143:475-476

Schafer CT, Winters GV, Scott DB, Picklington P, Cole FE, Honig C (1995) Survey of living foraminifera and polychate populations at some Canadian aquaculture sites: potential for impact mapping and monitoring. J Foram Res 25:236-259

Schindler, D.W. (1988) Effects of acid rain on freshwater ecosystems. Science 239:149-158.

Schindler, D.W., S.E.M. Kasian and R.H. Hesslein (1989) Biological impoverishment in lakes of the Midwestern and northeastern United States from acid rain. Environmental Science and Technology 23:573-580

Scoffin TP, Tudhope AW, Brown BE (1989) Corals as environmental indicators, with preliminary results from south Thailand. Terra-Nova 1:559-563

Shannon CE, Weaver W (1949) The mathematical theory of communication. Univ. Illinois Press, Urbana

Soule DF (1988) Marine organisms as indicators: reality or wishful thinking? In:Soule DF, Kleppel GS (eds) Marine organisms as indicators.Springer-Verlag, New York pp 1-11

Soule ME, Kohm KA (1989). Research priorities for conservation biology. Island Press, Washington, DC

Spellerberg IF (1991) Monitoring ecological change. Cambridge University Press, UK

Spies R (1984) Benthic-pelagic coupling in sewage-affected marine ecosystems. Mar Env Res 13:195-230

Steger R, Caldwell RL (1993) Reef flat stomatopods. In: Long-term assessment of the oil spill at Bahia Las Minas, Panama, synthesis report, volume II: technical report. Keller BD, Jackson JBC (eds) OCS Study MMS 90-0031.U.S. Department of Interior, New Orleans, La., pp 97-119.

Steneck RS, Lang JC, Kramer PA, Ginsburg RN (1997) Atlantic and gulf reef assessment (AGRA) rapid assessment protocol (RAP). Internet web site: http://coral.aoml.noaa.gov/agra EXIT disclaimer

Suter GW (1993) Ecological Risk Assessment. Lewis Publishers, Boca Raton, FL.

Swartz RC (1987) Toxicological methods for determining the effects of contaminated sediment on marine organisms, In: Dickson KL, Maki AW, Brugs WA (eds) Fate and effects of sediment bound chemicals in aquatic systems. Pergamon, New York, pp 183-198

Swartz RC, DeBen WA, Jones JK, lamberson JO, Cole FA (1985) Phoxocephalid amphipod bioassay for marine sediment toxicity. In: Cardwell RD, Purdy R, Bahner RC (eds) Aquatic toxicology and hazard assessment, Seventh Symposium, Philidelphia, PA: ASTM, pp 284-307

Szmant AM, Forrester A (1996) Water column and sediment nitrogen and phosphorous distribution patterns in the Florida Keys, USA. Coral Reefs 15:21-41

Thomas JD (1993) Biological monitoring and tropical biodiversity in marine environments: a critique with recommendations, and comments on the use of amphipods as bioindicators. J Nat Hist 27:795-806

Tomascik T, Sander F (1985) Effects of eutrophication on the growth of the reef-building coral Montastrea annularis. Mar Biol 87:143-155

Tomascik T, Sander F (1987a) Effects of eutrophication on reef-building corals. II.Structure of scleractinian coral communities on fringing reefs, Barbados. Mar Biol 94:53-75

Tomascik T, Sander F (1987b) Effects of eutrophication on reef-building corals. III. Reproduction of the reef-building coral Porites porites. Mar Biol 94:77-94

Tomascik T, Suharsono, Mah AJ (1994) Case histories: A historical perspective of the natural and anthropogenic impacts in the Indonesian Archipelago with a focus on the Kepulauan Seribu. In:Ginsburg RN (ed) Proc of Colloquium on Global Aspects of Coral Reefs. Univ Miami, pp 304-310

Turner SJ (1994) Spatial variability in the abundance of the corallivorous gastropod Drupella cornus. Coral Reefs 13:41-48

U.S. Environmental Protection Agency (USEPA) (1998) Clean water action plan: restoring and protecting America's waters. EPA-840-R-98-001, Washington, DC

U.S. Environmental Protection Agency (USEPA) (1996) Water Quality Protection Program for the Florida Keys National Marine Sanctuary - First Biennial Report to Congress 1996. USEPA, Office of Water, Washington, DC

U.S. Environmental Protection Agency (USEPA) (1992) Framework for Ecological Risk Assessment. EPA/630/R-92/001, USEPA, Office of Research and Development, Risk Assessment Forum, Washington, DC

U.S. Environmental Protection Agency (USEPA) (1990a) Biological criteria: national program guidance for surface waters. EPA-440/5-90-004, USEPA, Office of Water, Office of Regulations and Standards, Criteria and Standards Division, Washington, DC

U.S. Environmental Protection Agency (USEPA) (1990b) Near coastal program plan for 1990: estuaries, November 1990. EPA-600-4-90/033, USEPA, Washington, DC

Vail L (in press) Crinoids and other echinoderms as bioindicators of pollution in the Pulau Seribu reefs. In: UNESCO Reports in Marine Science, Proceedings of the UNESCO Coral Reef Evaluation Workshop, Kepulauan Seribu, Indonesia

Vobis H (1973) Rheotaktiches verhalten einiger Gammarus-arten bie verschiedenen sauerstoffgehald des Wassers. Helgolander Wissenschaftliche Meeresuntersuchungen 25:495-508

Warwick RM (1986) A new method for detecting pollution effects on marine macrobenthic communities. Mar Biol 92:557-562

Warwick RM (1988) The level of taxonomic discrimination required to detect pollution effects on marine benthic communities. Mar Poll Bull 19:259-268

Warwick RM, Clarke KR (1993) Increased variability as a symptom of stress in marine communities. J Exp Mar Biol Ecol 172:215-226

Wells SM (1995) Science and management of coral reefs: problems and prospects. Coral Reefs 14:177-181

Wenner AM (1988) Crustaceans and other invertebrates as indicators of beach pollution. In: Soule DF, Kleppel GS (eds) Marine organisms as indicators. Springer-Verlag, New York, pp 199-229

Weston DP (1990) Quantitative examination of macrobenthic community changes along an organic enrichment gradient. Mar Ecol Prog Ser 61: 233-244

White AT (1989) The association of Chaetodon occurrence with coral reef habitat parameters in the Phillipines with implications for reef assessment. Proc 6th Intl Coral Reef Symp 2:427-431

Widdowson TB (1971) Changes in the intertidal algal flora of the Los Angeles area since the survey by E. Yale Dawson in 1956-1959. Bull S Calif Ac of Sci 70:2-16

Wilson JG, Jeffrey DW (1994) Benthic biological pollution indices in estuaries. In: Kramer KJ (ed) Biomonitoring of coastal waters and estuaries, CRC Press, Boca Raton pp 311-324

APPENDIX 1

Scleractinian coral bioindicators. References in bold are references which specifically mention the bioindicator potential of the parameter in question, those in plain text are primary literature which supports the utility of the bioindicator, while those in italics are literature which presents contradictory evidence or shows the proposed bioindicator to be inappropriate.

Bioindicator	Protocol	Region	State	Season	References
% Hard Coral Cover, Benthic cover diversity indices	"Traditional" reef monitoring parameters. Generally calculated using data from line intercept transects, but occasionally use belt transects, quadrats, and even manta tow.	Pacific Caribbean Indian		NA	Dodge et al. 1982, DeVantier 1986, Gomez & Yap 1988, Aronson et al. 1994, English et al. 1994
Coral vitality/mortality indices	Various models, but all calculate an index based on ratios of live and dead hard coral colonies. Some use data from LIT's, others use "random" searches for coral colonies of particular species. No formal interpretive framework.	Caribbean Pacific	Florida Keys Hawaii Philippines	NA	Grigg & Dollar 1990, Dustan 1994, Gomez et al. 1994, Ginsburg et al. 1996
Coral growth rate	Measurement of coral growth rates as an indication of water quality. Confused literature - some suggest growth rates decline with organic pollution, others suggest growth rates may increase. No formal interpretive framework.	Caribbean Pacific Indian		NA	Brown 1988, Hudson 1981, Cortes & Risk 1985, Rogers 1990, Brown & Howard 1985, Tomascik & Sander 1985, Brown et al. 1990, Risk et al. 1995
Productivity and calcification profiles	Measurement of productivity and calcification profiles as an indication of water quality. No formal interpretive framework.	Caribbean Pacific Indian		NA	Barnes 1983, Brown 1988, Chalker et al. 1985, McLanahan 1997
Coral fecundity	Latest research from University of Guam	Caribbean Pacific	Guam	Dependent on local	Brown 1988,

and recruitment	looks at how different life-history stages of corals exhibit differential sensitivities to pollutants. Also, how different substances will differentially affect different stages in the reproduction/recruitment cycle. Formal interpretive framework under development.	Indian		spawning/ settlement condt's	Pearson 1981, Tomascik & Sander 1987b, Richmond 1993, 1994a, 1994b, 1995 & 1996, Peters et al. 1997
Zooxanthellae loss	Quantifying the occurence and extent of coral bleaching as a general bioassay of environmental stress on corals. No formal interpretive framework.	Caribbean Pacific Indian		NA	Brown 1988, Jones 1997
Coral diseases and cyanobacterial blooms	Monitoring the frequency and severity of occurances of coral diseases and cyanobacterial blooms. No formal interpretive framework.	western Atlantic	Florida	NA	Richardson 1997
Bioaccumulation of metals, phosphorus	Measurement of bioaccumulation of seawater contaminants in hard coral skeletons. No formal interpretive framework.	Caribbean Pacific Indian		NA	Dodge et al. 1984, LeTissier & Brown 1988, Hanna and Muir 1990
Physical damage	Measurement of physical damage to corals via transects or quadrates as an indicator of over use. The exact cause of physical damage is never totally certain.	Red Sea Caribbean		NA	Jameson et al. 1997, Hawkins and Roberts 1996, Chadwick-Furman 1996, Dixon et al. 1993

"No formal interpretive framework" means that the bioindicator in question has been proposed as a sensitive indicator of some environmental perturbation, but that a formal protocol for interpreting results has not yet been developed. For example, though coral bleaching or coral growth rates have been proposed as bioindicators, there are no guidelines for average growth rates or percentage of naturally-bleached colonies on a "healthy" reef versus growth rates or bleaching which signal water quality deterioration. By contrast, many freshwater biomonitoring programs have well-developed guidelines - for example, calculation of a numerical index, with a "formal interpretive framework" that a score of 20-25 indicates healthy river systems, 12-20 slightly impacted, etc..

APPENDIX 2

Fish bioindicators. References in bold are references which specifically mention the bioindicator potential of the parameter in question, those in plain text are primary literature which supports the utility of the bioindicator, while those in italics are literature which presents contradictory evidence or shows the proposed bioindicator to be inappropriate.

Bioindicator	Protocol	Region	State	Season	References
Butterflyfish (chaetodontids)	Monitoring hypothesis: for those species of butterflyfish which are obligate corallivores, a decline in the health of a reef, manifested by decreasing food quality of the stressed coral polyps, will result in a decrease in the abundance and diversity of these species and an increase in territory size, feeding rate and agonistic encounters as mated pairs attempt to maintain their nutritional intake by expanding their territories to include more coral colonies. After a time, feeding rates may decrease as more time is spent defending territories from neighboring pairs. Crosby and Reese (1996) outline a monitoring protocol which includes the use of 1-4, 30m line transects for visual census of butterflyfish abundance and live hard coral cover, as well as measurement of territory size, feeding and chasing behavior of individual pairs of target species. No formal interpretive framework.	Pacific	Hawaii Fiji	NA	**Reese 1981 & 1994,** **Hourigan et al. 1988,** **Nash 1989,** **White 1989,** **Crosby & Reese 1996,** Bell & Galzin 1984, Bouchon-Navaro et al. 1985, *Roberts & Ormond 1987,* *Roberts et al. 1988,* *Brown 1988,* *Jones & Kaly 1996,* *Erdmann 1997,* *Erdmann & Caldwell 1997*
Ectoparasites on coral reef fishes	Suggestion that the incidence of ectoparasitism on reef fishes should increase with deteriorating water quality. Used fish visual census technique of timed searches within 100m of shoreline. No formal interpretive framework.	Caribbean Pacific Indian		NA	**Evans et al. 1995,** Esch et al. 1975, *McVikar et al. 1988,* *Gray 1989*
Larval fish assemblages	Suggestion that the sensitivity of larval fishes, along with their position in the pelagic food web, make them excellent indicators of environmental perturbations. Collected using automated light traps. No formal interpretive framework.	Caribbean Pacific Indian		Dependent upon local spawning/ settlement conditions	**Doherty 1991**
Commercially valuable fish species as indicators of fishing	Several monitoring protocols include censusing abundance of commercially valuable fish species to gauge fishing pressure. Target groups include food fishes	Caribbean Pacific Indian		NA	**Dahl 1981,** **Hodgson 1997,** **McManus et al. 1997**

pressure	(Serranidae, Haemulidae) and aquarium fishes (Chaetodontidae). No formal interpretive framework.				
Organic contaminants and the development of fishes	Uses the occurrence of developmental defects in a demersal spawning fish as a bioindicator of pollution effects (damselfish *Abudefduf sordidus* in areas contaminated with PCBs and will also be looking in areas contaminated with dioxins). Preliminary data suggests that with increasing sediment PCB concentration there is an increase in the occurrence of developmental defects.	Pacific	Johnston Atoll	NA	Kerr (pers. com.)

"No formal interpretive framework" means that the bioindicator in question has been proposed as a sensitive indicator of some environmental perturbation, but that a formal protocol for interpreting results has not yet been developed. For example, though coral bleaching or coral growth rates have been proposed as bioindicators, there are no guidelines for average growth rates or percentage of naturally-bleached colonies on a "healthy" reef versus growth rates or bleaching which signal water quality deterioration. By contrast, many freshwater biomonitoring programs have well-developed guidelines - for example, calculation of a numerical index, with a "formal interpretive framework" that a score of 20-25 indicates healthy river systems, 12-20 slightly impacted, etc..

APPENDIX 3

Macrophyte bioindicators. References in bold are references which specifically mention the bioindicator potential of the parameter in question, those in plain text are primary literature which supports the utility of the bioindicator.

Bioindicator	Protocol	Region	State	Season	References
Macrophytes as metals bioaccumulators	Analysis of macrophytic algal tissues for bioaccumulation of heavy metal seawater contaminants. Utilizes atomic absorbtion spectrophotometry. Inconclusive results from coral reef study, shown effective in temperate marine systems. No formal interpretive framework.	Caribbean Pacific Indian		NA	**Brown & Holly 1982,** Bryan & Hummerstone 1973, Phillips 1974
Monitoring of macrophytic algal "blooms"	Several volunteer reef surveys (Aquanaut and Reef Check) suggest recording macrophytic algal blooms as an indication of high nutrient inputs on coral reefs (or overfishing of fish and invertebrate grazers). No formal interpretive framework.	Caribbean Pacific Indian		Not specified, though blooms are often highly seasonal - often correspond with wet season.	McManus et al. 1997, Hodgson 1997

"No formal interpretive framework" means that the bioindicator in question has been proposed as a sensitive indicator of some environmental perturbation, but that a formal protocol for interpreting results has not yet been developed. For example, though coral bleaching or coral growth rates have been proposed as bioindicators, there are no guidelines for average growth rates or percentage of naturally-bleached colonies on a "healthy" reef versus growth rates or bleaching which signal water quality deterioration. By contrast, many freshwater biomonitoring programs have well-developed guidelines - for example, calculation of a numerical index, with a "formal interpretive framework" that a score of 20-25 indicates healthy river systems, 12-20 slightly impacted, etc..

APPENDIX 4

Coral reef epifaunal bioindicators. References in bold are references which specifically mention the bioindicator potential of the parameter in question, those in plain text are primary literature which supports the utility of the bioindicator, while those in italics are literature which presents contradictory evidence or shows the proposed bioindicator to be inappropriate.

Bioindicator	Protocol	Region	State	Season	References
Sessile reef community	Utilizes data from line intercept transects of sponge, gorgonian assemblages. Calculation of two well-known diversity indices, H' and J', and comparison of their relative values allows a classification of environmental conditions (favorability and predictability) on a reef.	Caribbean	Cuba	NA	**Alcolado et al. 1994**
Heterotrophic macroinvertebrates	Largely undeveloped, based upon the well-substantiated observation that many pollution-stressed reefs undergo an "ecosystem shift" from those dominated by coral-algal symbionts towards those dominated by heterotrophic macroinvertebrates, especially scavengers, filter feeders, and internal bioeroders. Abundance measures of many of these groups are included in several current monitoring schemes, but no formal interpretive framework is in place at this time.	Caribbean Pacific Indian		NA	**Dahl 1981,** **Dustan & Halas 1987,** **Risk et al. 1994,** **Hodgson 1997,** **McManus et al. 1997,** Tomascik & Sander 1987a, Kinsey 1988, Tomascik et al. 1994, Vail (in press)
Internal bioeroders	Studies in both the Caribbean and Pacific have shown conclusively that the proportion of rubble (or live coral colonies) invaded by bioeroding sponges and bivalves, as well as the number of invasions per rubble sample increase with increasing eutrophication. Not formally proposed	Caribbean Pacific Indian		NA	Rose & Risk 1985, Sammarco & Risk 1990, Risk et al. 1995, Holmes 1997

	as bioindicator, but obvious potential.				
Coelobites (reef cavity-dwellers)	Shown that coelobites such as foraminifers, bryozoans, tunicates, molluscs and serpulid worms decrease in abundance with proximity to an offshore oil drilling well-head. Developed numerical index with points assigned for presence/absence and abundance of various coelobites in each rubble piece, with resulting index used to classify reef health.	Pacific	Philippines	NA	Choi 1982
Foraminifers	Community response to gradually increasing nutrient flux, whether natural or anthropogenic, favors phytoplankton, bnethic algae, and heterotrophic taxa lacking algal symbionts, rather than taxa that utilize algal symbionts for enhanced growth and calcification. Benthic succession along a nutrification gradient is a predictable response that has been commonly observed in foraminiferal assemblages.	Caribbean Pacific Indian		NA	**Hallock-Muller 1996, Hodgson 1997, Cickey et al. 1996**
Bioaccumulation in molluscs	Very well-developed bioassay in temperate systems (eg, Musselwatch), not very developed in reefal areas. Filter-feeding bivalves and grazing gastropods are sampled for metals bioaccumulation using atomic absorbtion spectrophotometry. No formal interpretive framework.	Caribbean Pacific Indian		NA	**Brown and Holly 1982,** Goldberg et al. 1978, Hungspreugs & Yuangthong 1984
Stomatopod crustaceans	Bioassay still under development. Studies from both the Caribbean and Pacific show conclusively that stomatopod abundance, diversity, and recruitment are strongly negatively correlated with various pollution measures. No formal interpretive framework.	Caribbean Pacific Indian		NA	**BSteger & Caldwell 1993, Erdmann 1997b, Erdmann & Caldwell 1997,** Erdmann & Sisovann (in press)
Amphipods	In addition to acute and chronic sensitivities to pollutants and toxicants, amphipods exhibit a number of altered behavioral responses to sublethal levels of a variety of compounds that can cause reduction or elimination of the	Caribbean Pacific Indian		NA	**Thomas 1993, Oakden et al. 1984, Baker 1971, Sandberg et al. 1972, Percy 1976,**

	population. Amphipods are more sensitive than other species of invertebrates (decapods, polychaetes, molluscs, and asteroids) to a variety of contaminants. Amphipods also show responses to dredging, shoreline alteration, fishing practices, salinity, and dissolved oxygen.				**Linden 1976a & b, Lee et al. 1977, Ahsanullah 1976, Swartz et al. 1985, Swartz 1987, Barnard 1958 & 1961, McCluskey 1967 & 1970, Widdowson 1971, Vobis 1973**
Gastropod imposex	Well-developed bioassay. Gastropod imposex (imposition of male sexual characters on females) is extremely sensitive indicator of exposure to tributyl tin. Occurence and severity of imposex in a particular population is quantifiedusing both frequency of imposex in females and relative penis size index - mean ratio of penis weight to body weight for all females divided by same ratio for males.	Caribbean Pacific Indian		NA	**Ellis & Pattisina 1990, Foale 1993, Gibbs & Brya 1994, Evans et al. 1995**
Corallivores	Records abundance of corallivores such as crown-of-thorns starfish (*Acanthaster planci*) and *Drupella gastropods*. No formal interpretive framework.	Pacific		Dependent upon local spawning/ settlement conditions	**Erdmann 1997b,** Gajbhiye et al. 1987, Herrnkind et al. 1988, Garrity & Levings 1990

"No formal interpretive framework" means that the bioindicator in question has been proposed as a sensitive indicator of some environmental perturbation, but that a formal protocol for interpreting results has not yet been developed. For example, though coral bleaching or coral growth rates have been proposed as bioindicators, there are no guidelines for average growth rates or percentage of naturally-bleached colonies on a "healthy" reef versus growth rates or bleaching which signal water quality deterioration. By contrast, many freshwater biomonitoring programs have well-developed guidelines - for example, calculation of a numerical index, with a "formal interpretive framework" that a score of 20-25 indicates healthy river systems, 12-20 slightly impacted, etc..

APPENDIX 5

Other bioindicators. References in bold are references which specifically mention the bioindicator potential of the parameter in question, those in italics are literature which presents contradictory evidence or shows the proposed bioindicator to be inappropriate.

Bioindicator	Protocol	Region	State	Season	References
Nitrogen isotope ratios	Stable isotope ratios of $^{15}N/^{14}N$ (denoted d ^{15}N) in reef organism tissues have been shown to be an excellent indicator of human faecal waste inputs on coral reefs. Calibration of d ^{15}N is necessary for each specific organism and region, but very powerful and accurate means of assessing this form of organic enrichment. Uses mass spectrophotometer to measure d ^{15}N.	Caribbean Pacific Indian		NA	**Risk et al. 1994, Dunn 1995, Risk & Erdmann (in press)**
Soft-bottom benthic community structure	Used extensively in temperate marine ecosystems, but not yet applied to coral reefs. Large body of work shows consistent, predictable responses in soft bottom community structure to increasing pollution, including decrease in species richness, increase in total number of individuals, reduction in the mean size of the average species or individual, changes in shape of log-normal distribution of individuals among species, and increased variability in species diversity indices. Needs further research to apply to coral reefs.	??		NA	**Pearson & Rosenberg 1978, Gray & Mirza 1979, Gray, 1981 & 1989 Pearson et al. 1983, Warwick 1986, Bilyard 1987, Clarke 1993, Warwick & Clarke 1993,** *Brown 1988, Weston 1990*
FACT'97 coastal indicators	The change in coral reef community dynamics indicator used by FACT is the coral reef/hard bottom monitoring facet of the FKNMS water quality monitoring program (Table 3.3). Relating other FACT indicators to coral reef ecosystem integrity will require the development of special indices and calibration.	western Atlantic	Florida	NA	**Bergquist et al. 1997**

Map-based indicators of potential threats to coral reefs	While still experimental, the "Reefs at Risk" indicators flag problem areas around the world where - in the absence of good management - coral reef degradation might be expected, or predicted to occur shortly, given ongoing levels of human activity. Results are based on a series of distance relationships correlating mapped locations of human activity, such as ports and towns, oil wells, coastal mining activities and shipping lanes (component indicators) with predicted risk zones of likely environmental degradation. Detailed sub-national statistics on population density, size of urban areas, and land cover type were also incorporated into the analysis. Data on rainfall and topography are used to estimate potential runoff within watersheds, from inland deforestation and agriculture. To make these indicators approach reality, a time factor must be incorporated into them, otherwise there is no feeling of urgency to the threats. Some of the map-based indicator assumptions need work as they are confounded by other factors or simply invalid.	Global	Global	NA	**Berke et al. 1998**
RAMP indicators for assessing the human impacts (social, cultural and economic) on coral reefs	Indicators are organized according to proximity to the designated reef (e.g., national, regional and local), context (political, socioeconomic and cultural), reef uses (fishing, mining, tourism/recreational, etc.), and governance (institutional frameworks, knowledge bases, plans, implementation, monitoring and evaluation). A guide for information acquisition and subsequent coding for inclusion in ReefBase was also developed. Relating RAMP indicators to coral reef ecosystem integrity will require the development of special indices and calibration.	Pacific Caribbean	Philippines Jamaica	NA	**Pollnac, 1997**