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Establishing reference conditions for the diagnostic monitoring and assessment of coral reefs

Key words: coral reef • reference condition • biogeographic region • classification • diagnostic monitoring and assessment • index of biotic integrity • biocriteria

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Abstract Minimally impaired reference conditions are critical for detecting cumulative impacts and for effective monitoring and assessment of coral reefs. They are especially important for future diagnostic monitoring and assessment programs using indexes of biotic integrity (IBI) and the biocriteria process. Reference conditions for diagnostic monitoring and assessment should be defined in terms of IBI metrics that are known to provide clear, consistent, and interpretable signal about the condition of sites. Reference conditions can be based on: historical data, paleoecological data, experimental laboratory data, quantitative models, biogeographical regional reference sites and best professional judgement. Establishing reference condition is difficult and imperfect because knowledge of historical condition is limited. Moreover, knowledge about the history of disturbances at most sites is at best fragmentary making definition of what is natural impossible.
The use of information from minimally impaired reference sites combined with best professional judgement will be critical in establishing IBI metric reference conditions, because at present, other sources of data are minimal. Potential minimally impaired reference sites are recommended for coral reefs under United States jurisdiction. Special efforts should be made to establish no-take marine sanctuaries in unprotected reference sites. The longer we delay in selecting and conserving relevant reference sites and determining appropriate coral reef reference conditions, the more difficult it will be to define acceptable condition and use biological assessments to limit further deterioration of coral reefs.

Introduction

The goal of coral reef assessment is to detect and understand change in coral reef biological systems that result from the actions of human society. One primary objective is to detect when management decisions designed to improve coral reefs actually work (Jameson et al. 2002). But change with respect to what? Just as economic analyses define a standard (e.g., 1950 dollars) against which inflation can be judged, coral reef biological assessment must have a standard against which the conditions at one or more sites of interest can be evaluated. This standard, or reference condition, provides the baseline for site evaluation and can be used to make intelligent statements about changes to coral reefs around the world. Without a minimally impaired reference condition, there is the possibility of succumbing to the shifting baseline syndrome (Pauly 1995, Sheppard 1995, Jackson 1997, Bohnsack 2003) making it impossible to detect cumulative impacts. This syndrome occurs when reference conditions are changed with each new monitoring program as a result of the researcher's historical frame of reference with respect to the condition of the coral reef (Fig. 1).

For the purposes of this discussion, a coral reef is defined as a marine limestone structure built by calcium-carbonate secreting organisms which, with its associated water volumes supports a diverse community of predominately tropical affinities (modified from Hatcher 1997).

In multimetric biological assessment, such as employed in the use of the index of biological integrity – IBI (Karr and Chu 1999, Jameson et al. 2001), reference condition equates with biological integrity. IBI's compare the biota of a predetermined reference condition, with minimal human influence, to the biota of physically similar sites influenced by the activity of humans. Biological integrity is defined as the condition at sites able to support and maintain a balanced, integrated, and adaptive biological system having the full range of elements and processes expected for that biogeographical region and type of environment. Biological integrity is the product of ecological and evolutionary processes at a site with minimal human influence (determined by best available information). Protecting biological integrity is a primary objective of the U. S. Clean Water Act. The value of IBI is that it enables us to detect and measure divergence from biological integrity. When divergence is detected, society has a choice: to accept divergence from integrity at that place and time, or to restore the site (Karr and Chu 1999). The challenge for humans (and other creatures) is not to throw the ecological balance off and destroy themselves in the process. This will require integrated ecological thinking and political leadership on a global scale (Jameson et al. 1995, Karr 2000, Jameson et al. 2002).

So, where are we on the ecological balance with respect to human impacts on coral reefs? Without minimally impaired reference conditions, we will never know — until it is too late. We may even have already tipped the balance (Ginsburg 1994, Jameson et al. 1995, Jackson 1997, Bryant et al. 1998, Karr 2000, Buddemeier 2001, Guinotte et al. 2003).

To face this challenge we can only do our best with the cards as they have been dealt by history. Determining coral reef biological integrity and minimal human influence with our best available knowledge is going to be difficult and imperfect because our information is historically limited (Jackson 1997, Jackson et al. 2001, Bohnsack 2003) and we really do not understand what is natural (Woodley 1996, Sapp 1999).

Regardless of the inadequacies, we must define coral reef reference conditions with best available knowledge and modify our view, if necessary, as understanding of relationship between cumulative human coral reef impacts and ecosystem function improves. In addition, the concept of reference condition should be related to a relevant coral reef classification (Jameson et al. in ms.). Not trying to find the best available information and establish minimally-impaired reference conditions simply makes it harder for those coming 50 years from now to understand what things used to be like.

The purpose of this paper is to initiate a discussion of how we might define reference conditions for the diagnostic monitoring and assessment of coral reefs using IBI's. We discuss the characteristics of reference conditions. We explore the strengths, weaknesses and opportunities of various approaches for establishing reference conditons and recommend specific approaches that should work best for coral reef IBI's. We outline the major steps for selecting reference sites and recommend reference site candidates for coral reefs under United States jurisdiction. Finally, we discuss some of the reference condition challenges for coral reefs under United States jurisdiction.

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

While this paper focuses on developing reference conditions for coral reef IBI metrics, the approaches discussed can also be applied to developing reference conditions for non-diagnostic monitoring programs (i.e., Reef Check, the Global Coral Reef Monitoring Network (GCRMN), and the Atlantic and Gulf Rapid Reef Assessment (AGRRA)).

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

Characteristics of reference conditions

At least five interrelated aspects should be considered when establishing an approach to define reference condition for coral reef IBI metrics.

1. Reference condition should be grounded, to the greatest extent possible, in knowledge of the character of a place with minimal human influence. Today, no coral reef is untouched by human influence. Global climate change (i.e., increasing CO_2 concentrations in the ocean, increasing sea surface temperature, and sea level rise), and local and regional effects of diverse human actions (i.e., overfishing, sedimentation, nutrification, physical damage, etc.) affect reefs to varying degrees throughout the world (Ginsburg 1994, Jameson et al. 1995, Jackson 1997, Bryant et al. 1998, Karr 2000, Buddemeier 2001, Jameson et al. 2002, Guinotte et al. 2003). Despite considerable difficulty in defining natural and quantifying minimal human influence we must make our best effort. Reference conditions can not be based solely on current conditions where these conditions reflect fundamentally altered coral reefs (Jackson 1997, Jackson et al. 2001, Bohnsack 2003).

2. Reference condition should be defined in terms of IBI metrics that are known to provide clear, consistent, and interpretable signal about the condition of sites. As such, reference conditions will probably need to be established first for benthic macroinvertebrates (Table 1), as this IBI shows great promise and is furthest along in

development (Jameson et al. 2001). Not all of the attributes listed in Table 1 would be developed into metrics and used in a coral reef benthic macroinvertebrate IBI.

Metrics are attributes with clear and consistent dose-response signals across a gradient of human influence.

Table 2 lists the best mix of metrics for an IBI and this mix should be used as a starting point for a coral reef benthic macroinvertebrate IBI.

Reference conditions might also be needed for IBI's using sessile epibenthos, macrophytes, phytoplankton, zooplankton and fishes depending on their promise and development (see Jameson et al. 2001 for listing of potential metrics).

It should be noted that extreme caution must be exercised when using commercially important fishes for IBI metrics as coral reef species in most areas are drastically over fished (Ault 1998, Bohnsack 2003). An understanding of historical fishing impacts for the specific area is required before considering commercially important fishes for any type of IBI metric.

3. Within biogeographic regions, we will need to define IBI metric reference conditions for each coral reef zone we are interested in monitoring (Jameson et al. in ms.) because zones are subject to different environmental conditions such as wave and light energy (Graus and Macintyre 1989). Just as a benthic invertebrate IBI for streams would have

different expectations for a pool vs. a riffle sample. The number of and kind of stream insect taxa, for example, will differ among zones — as will the number and kind of coral reef benthic macroinvertebrates in the fore reef zone vs the reef flat zone. Different measures and scoring criteria will also be required depending on what zone is sampled.

4. Each metric reference condition in the IBI for a coral reef zone should represent large numbers of defined populations. Each coral reef zone should be homogeneous enough that we can define, for that group of important metrics that make up the IBI, what a minimally disturbed reef biota should be like.

5. The search for places that can be used to clearly define the character of minimally impaired sites should not be limited by existing political boundaries. Wherever possible, governments should share reference condition information. Such coordination has both political and scientific value and increases the amount of information and expertise available to set biological criteria. It also increases the probability that reference conditions will be widely representative and that they will represent sites with minimal human influence. International cooperation on defining reference conditions also increases the political acceptability of reference conditions or biological criteria and reduces opportunities for landowners and pollution dischargers to avoid regulatory controls (Hughes 1995).

Approaches for determining reference conditions

The process of establishing reference condition can be based on at least six major kinds of information or approaches: historical data, paleoecological data, experimental laboratory data, quantitative models, best professional judgement and reference sites (Hughes 1995). The utility of each approach varies with environment type and biogeographical region. Lakes, for example, provide ample opportunity to use paleoecological data but streams do not. Streams and fish have long been sampled in some regions but not in others so the availability of historical data sets may not be consistent among regions. Similar points can be made about the relative merit of these six approaches for coral reef studies and in each biogeographic region scientists and managers will have to make due with some mosaic of the set to best use existing knowledge. Each one has its own particular strengths, weaknesses and opportunities. Each one also makes use of classification (Jameson et al. in ms.) to some degree.

1. Historical Data

Historical data can be useful to a limited degree in establishing coral reef reference conditions and such data can be used for describing trends. Unfortunately, historical data for coral reef organisms in general, and potential IBI metric organisms in particular, are very limited (Jackson 1997, Jackson et al. 2001, Bohnsack 2003). What data is available is primarily limited to coral and commercially important fishes   neither of which will likely play a significant role in coral reef IBI development (Jameson et al. 2001).

Fig. 2 illustrates the dramatic change in local fisheries resources (sea urchins, sea turtles and fish) with respect to human population growth in Jamaica. In the Caribbean, history shows that coastal ecosystems were severely degraded long before ecologists began to study them (Jackson 1997, Jackson et al. 2001) making the availability of historical data extremely scarce.

- Large vertebrates (green and hawksbill turtles, manatee, and Caribbean monk seals) were decimated in central and northern Caribbean by 1800 and elsewhere by 1900.

- By the mid 19th century: subsistent overfishing decimated fish populations when human populations were less than one fifth their numbers today, local fisheries accounted for a small fraction of the fish consumed on Caribbean islands.

- Herbivores and predators were reduced to very small fishes and sea urchins before the 1950's when intensive scientific investigation began.

The difficulties of establishing reference conditions with limited historical information are profound and illustrated in Figure 1 (Bohnsack 2003).

Historical data have several limitations. They may be limited to only a single assemblage and they must incorporate a large number of samples to be very useful. In some cases the data may be intractable, either because they are difficult to obtain or difficult to work with. Historical data in many cases may not be available in sufficient quantity or quality (especially the latter). Historical data may also be collected with different methods and for different purposes (neither of which are described). Such differences can make comparisons with current samples problematic. Some collections may have been taken from historically disturbed sites, and such habitat information may be missing or incomplete. All historical data should be examined carefully (Hughes 1995).

2. Paleoecological Data

A special case of historical data is the information stored in coral reef sediments, particularly diatom and foraminifera assemblage data. Foraminifera and diatoms are most affected by water quality changes and such information can be useful in assessing changes in climate, salinity, pH, and nutrients (Glynn 1973, Hallock 1996, Hallock 2000 a,b,c). Constituent analyses of foraminifera sediment can address questions of historical change and reference-site suitability (Hallock 2000 a,b,c). Analysis of live larger foraminiferal assemblages can indicate the suitability of sites for organisms with algal symbionts. Foraminifera populations, such as those of *Amphistegina*, respond similarly to corals with respect to bleaching and other stressors (Hallock 1996, 2000 a,b,c). The paleoecology of benthos and zooplankton is less advanced than for foraminifera and diatoms and it is essential to obtain a sufficiently long core and date it to ensure that the reference condition represents an appropriate historical period (Hughes 1995). Figs. 3 and 4 demonstrate the use of diatoms in establishing reference condition in a freshwater lake situation.

The FORAM Protocol (Hallock 1996, Hallock 2000 a,b,c) presently uses a 1996 historical reference condition for Florida locations but there is a recognized need to historically improve this reference condition (Hallock, personal communication).

3. Laboratory data

Laboratory data, although not typically viewed as useful in determining reference conditions in fresh water situations, may be valuable for coral reefs. Relationships between test species and specific toxins, temperatures, nutrients, and dissolved oxygen concentrations can indicate stressor levels that are harmful to coral reef communities. Laboratory data are unlikely to offer sufficiently robust information from which to develop reference conditions for entire assemblages or communities. Laboratory water quality data are especially unsuited for establishing reference conditions for systems disturbed by other stressors, such as structural, hydrological, and biological alterations. Instead, laboratory data are probably most useful for screening out reference sites selected by other means or for improving model predictions (Hughes 1995).

4. Quantitative models

We must strive to develop reference condition quantitative models from field and historical data. These models become increasingly useful and accurate as the database size and complexity increase. It may be possible to estimate coral reef reference conditions through curve fitting by plotting metric values against well-distributed disturbance values or natural variables. Fausch et al. (1984) used such an approach to develop maximum species richness lines for stream fish assemblages by plotting against stream size (Fig. 5). Hughes et al. (1993) plotted percent native freshwater fish species against physical habitat quality to determine expected conditions at minimal disturbance (Fig. 6).

For coral reefs this general approach can also be expanded to multivariate linear regression models, as long as the relationships are linear or transformable and the data are of sufficient quality. Nonlinear models are also feasible. Outliers, uneven distribution of data, and the absence of data from sites with minimal human influence can greatly distort such models. It may be useful to examine residuals and patterns in the data that may reveal other predictor variables. Models developed in such a manner should not be extended beyond the data, the coral reef classification, or the biogeographic region from which the data were collected (Hughes 1995). Agent based coral reef models (now under exploration) have the potential to recreate historical coral reef conditions and be useful in the establishment of reference conditions (J. W. McManus, personal communication).

5. Reference sites

Probably the most promising way to define reference conditions for coral reef IBI metrics is via the use of minimally impaired reference sites.

All coral reefs of the world, and hence potential reference sites, suffer from a mix of human impacts (Ginsburg 1994, Jameson et al. 1995, Bryant et al. 1998, Jameson et al. 2002). Some locations have more stressors than others and the historical duration of impacts varies among locations. The challenge is to identify the least impaired sites and use their biological qualities to define reference conditions for specific coral reef IBI metrics (Tables 1 and 2). The conditions at reference sites should represent the best range of conditions with minimal human influence that can be achieved within a classification category (coral reef zone) for the biogeographic region. Finding coral reefs with minimal human influence will be difficult, considering our limited historical information, lack of understanding of what is natural, and the pervasive influence of humans. The goal is to find the best available sites to establish the baseline condition that defines biological integrity, the best reference sites available for the biogeographic region.

Caution should be exercised with respect to using resilient reefs (West and Salm in press) for reference sites as the fact that they are categorized as “resilient” suggests that they have been subjected to stressors and are not located in minimally impaired environments.

The use of minimally impaired reference sites for generating IBI metric reference conditions has limitations. Depending on the degree of coral reef classification (resolution), reference conditions may incorporate considerable variability because of scale and in some biogeographic regions this variability may be unsatisfactory (Hughes 1995).

Pitfalls to watch out for in using reference sites for coral reef diagnostic monitoring and assessment include:

- using local sites that are degraded rather than looking over the wider biogeographically similar area for minimally impaired sites;

- arbitrarily selecting reference sites without adequate screening or site evaluation;

- and ranking sites inaccurately so that degraded sites are put into reference sets.

For coral reef IBI metrics, the use of reference sites is going to be a primary source of reference condition information and critical to the biocriteria process. Table 3 describes a general method for selecting reference sites. Steps are listed in order of recommended occurrence. The process is not linear, but iterative and one must often return to earlier steps to surmount obstacles or to cull choices.

Remote coral reefs will likely be the best candidates for minimally impaired reference sites. The characterization and long-term study of these areas is critical for establishing and maintaining reference conditions. The coral reefs under U.S. jurisdiction listed in Table 5 have the potential to be reference sites (Jameson et al. 1998). Top priority should be given to confirming, documenting and conserving their minimally impaired condition.

If the sites we expect to use to estimate reference condition are disturbed, our ability to make such estimates will be compromised.

While governments may prefer reference sites within national political boundaries, reference sites may also have to be established in foreign waters. Effective protection mechanisms for reference sites will need to be developed and adequately funded.

6. Best professional judgment

Best professional judgement is critical to all the above approaches for determining reference conditions, whether it involves selection of biogeographic regional reference sites, the evaluation of historical data and experimental results, or the treatment of outliers and data patterns in models. A special case of professional judgement is the convening of expert panels to determine reference condition. Another example is peer review of the data and evaluations. As with quantitative models, the quality of the judgement is a function of the expertise of the scientists and the quality of the data supplied to them (Hughes 1995). We recommend selection of panelists and reviewers with opposing biases and different professional backgrounds to ensure different points of view, and to increase the credibility of the product in the eyes of the public.

Discussion

The relationship of reference condition to the IBI

Reference condition equates with biological integrity. A coral reef system should be self-regulating through time. An adaptive system can absorb many non-human, and some of the human stresses that occur. It is important for biologists to determine whether the coral reef systems they manage are in acceptable or unacceptable condition if they are to conserve and restore them, or communicate with the public about them. There are several challenges in doing so.

Many components of ecological and biological systems are variable, but at the same time many are not, especially when viewed across a gradient of human influence. The challenge is to find out what those attributes/metrics are, create IBI's with them and establish reference conditions for them (Jameson et al. 2001).

Significance vs. power considerations are of concern (i.e., with what certainty do we know the coral reef system does not have biotic integrity vs. how confident are we that it does). However, it is more important to understand biological consequence than it is to find statistical significance (Karr and Chu 1999). The process of developing metrics and applying scoring criteria in coral reef IBI’s and doing this across 8 to 12 metrics gives the kind of power that is important. Although individual metrics may be quite variable, the aggregate expression of biological metrics produced with an IBI yields much lower variability (Karr and Chu 1999).

Ecosystem parts and processes are important indicators of coral reef biotic integrity. Karr et al. (1986) show that both can be applied in fresh water situations. We can’t ignore the processes because they are the rates of things happening that shape the system. On the other hand, the parts are also important (e.g., it makes a big difference whether we have high production (a process) of shark (one part) or grouper (an alternate part) in the Florida Keys National Marine Sanctuary).

To maintain objectivity, we should understand the biological meaning of the levels of coral reef IBI’s rather than as some arbitrary percentage of the maximum reference condition. For example, in the Pacific NW results indicate that a benthic IBI based on insects needs to attain a minimum level of 35 (range 10 to 50) if one hopes to sustain healthy salmon populations in a watershed (J. R. Karr, unpublished data).

The relationship of human influence to nature

Coral reef scientists and managers have yet to reach consensus (and probably never will) on quantifying and defining what is natural (Woodley 1996, Sapp 1999). So to determine what minimal human influence or minimal impairment really means with respect to a natural system that humans are a part of requires a judgement as to when humans over step their ecological boundaries.

It is necessary to address this philosophical question, if biocriteria are to have any consistent meaning. In defining biological criteria, managers must strike a balance between the natural restoration of a coral reef resource and the fact that human activity affects the environment. Continual monitoring should provide the feedback necessary to make reference condition and interim criteria adjustments as warranted during the restoration process.

The role of politics

Given any coral reef reference condition data set, the role of scientists and government is distinct when designating the number signifying acceptable or unacceptable condition. We do not believe that scientists should be making these decisions. The task for coral reef scientists is to define the index, show how it behaves on various human influence scales, define the biological results that come from numbers and then have it work through the policy process to determine what the acceptable levels are. Scientists should clearly state their opinion regarding acceptable levels but not make the decisions. That is a public policy decision ostensibly implemented by political leaders and agency staff to serve the desires and needs of the general public under the law. Do the people want snappers or groupers? Do we want amphipods or no amphipods? Intolerant taxa or no intolerant taxa? Top predators or not? As scientists, we can define the levels for each of those things to be present or not, relatively healthy or not and society should make the judgements about what level is desired in the city as opposed to in a national marine sanctuary.

Conclusion

To make coral reef biological monitoring and assessment more effective — that is, to get information in the most cost-effective manner that can provide an early warning mechanism and a diagnostic function — biologists need to document and understand dose-response relationships between particular biological attributes and human influence (Tables 1 and 2). They need to identify metrics that respond to human disturbance and not just to geographical differences among regions. They must concentrate their efforts on sampling sites that have been subject to different intensities and types of human influence and compare these to sites with minimal human influence or other reference conditions. Finally, they must chose a small set of metrics that provide reliable signals about the effects of human activities in the biogeographic regions. Metrics must be chosen according to their ability to distinguish between different types and intensities of human actions. By integrating those metrics into a multimetric index, we have a scientifically sound and policy-relevant tool to improve the management of coral reefs. Reference conditions are the critical baseline upon which all this is compared (Jameson et al. 1998, 2001, in ms.).

There is no doubt it will be challenging to define reference conditions for coral reef IBI's using the approaches described in this paper. The use of information from minimally impaired reference sites combined with best professional judgement will be critical in establishing IBI metric reference conditions, because at present, other sources of data are minimal. It is fortunate that the most promising organisms for coral reef IBI metrics (i.e., benthic macro-invertebrates) are those which have not been over-exploited by humans.

We urge diligent objectivity and serious thought in determining coral reef IBI metric reference condition. Manager's jobs are to help citizens decide what they will do about scientist's best assessments of existing conditions and trends. Too often biologists have acquiesced and let policy matters influence their assessments (Saap 1999). This muddies the biological assessments, obscures the difficult policy decisions needed, and typically results in continued degradation of biological integrity.

Therefore, biological criteria should be set as high as the reference condition data will allow. It is the manager's responsibility, not the biologist's, if a majority of sites are in unacceptable condition or experiencing unacceptable trends. We are not fulfilling our responsibility to coral reef systems if we state ecosystems have biological integrity when they do not.

Two of our professional responsibilities are to alert managers and the public if our data indicate ecosystem deterioration and to advocate changes in management practices to correct those conditions. The fundamental question for coral reef biologists today is not whether we can turn the clock back to an era when most systems had biological integrity, but whether we can slow the continued rapid degradation of the environment and the concomitant loss of biological integrity.

The longer we delay in selecting and conserving relevant reference sites and determining appropriate coral reef reference conditions, the more difficult it is to define acceptable condition and use biological assessments to prevent further deterioration of coral reefs.

Acknowledgements

This research was funded by the U.S. Environmental Protection Agency under contract (8W 0622-NASX) to Coral Seas Inc. — Integrated Coastal Zone Management. JRK acknowledges support of the USEPA/NSF Water and Watersheds Program (Grant 825284010) and the Consortium for Risk Evaluation (CRESP) through Department of Energy Cooperative Agreement #DE-FCO1-95EW55084. We thank, M Chiappone and two anonymous peer reviewers for constructive comments on the manuscript and JA Bohnsack for historical fishing data.

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Fig. 1 Nassau grouper landings from commercial fishing in Cuba and recreational headboats in the Florida Keys, USA over one decade 1980-1989 (A), two decades 1970-1989 (B), and three decades 1960-1989 (C) (Bohnsack 2003). Using the Cuban data from the decades 1970-1989 (B), a hypothetical reference condition of about 2,000 metric tons could be inferred. However, when put in the context of the three decades data of 1960-1989 in (C), it shows that the hypothetical 2,000 metric ton reference condition was in reality only a short-term plateau in a much longer historical decline of grouper resources.

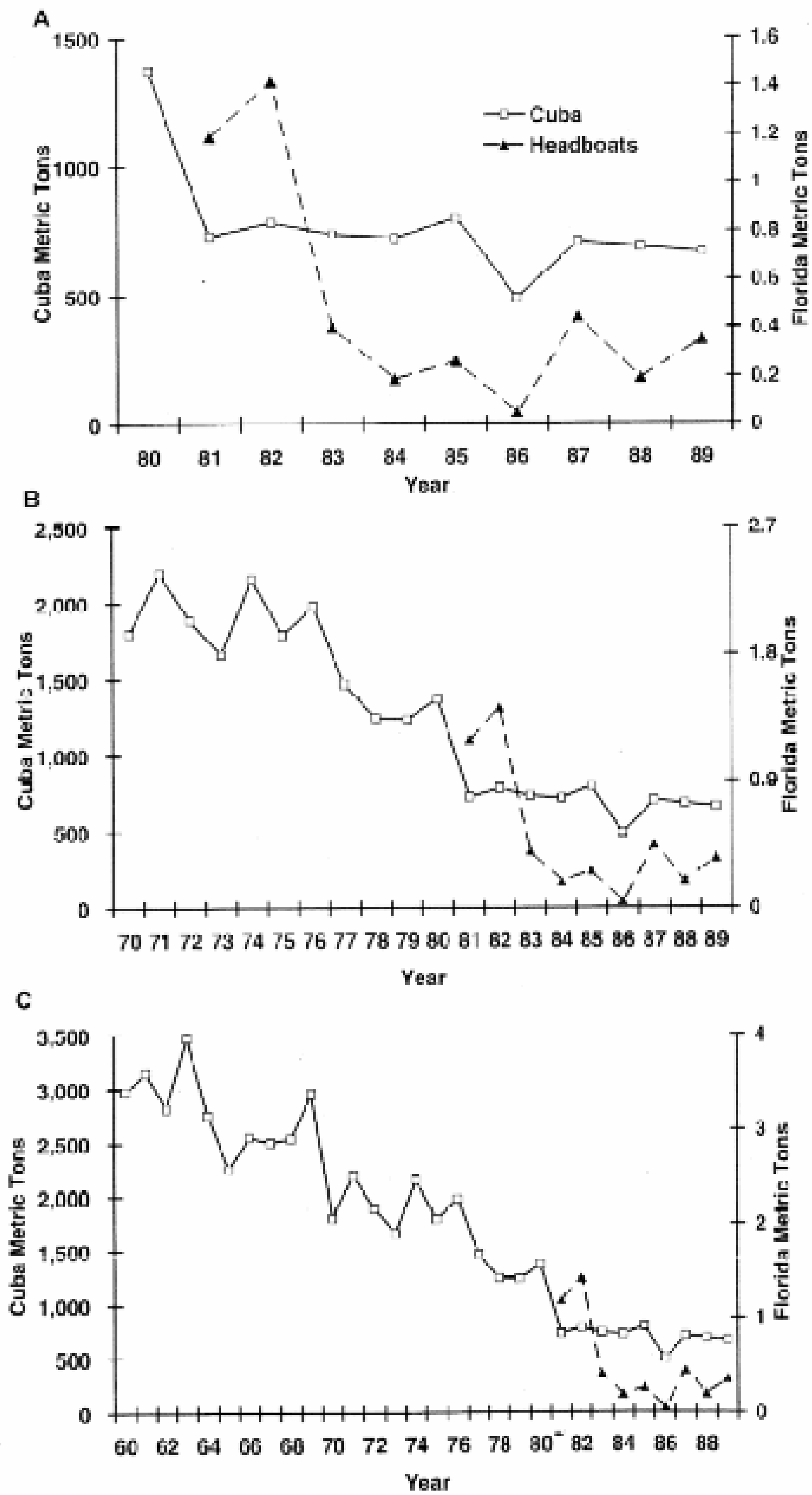
A
Cuba
Headboats
Cuba Metric Tons
Florida Metric Tons
Year
80
81
82
83
84
85
86
87
88
89
1500
1000
500
0
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
B
Cuba Metric Tons
Florida Metric Tons
Year
2,500
2,000
1,500
1,000
500
0
2.7
1.8
0.9
0
70 71 72 73 74 75 76 77 78 79 80 81 82 83 84 85 86 87 88 89
C
Cuba Metric Tons
Florida Metric Tons
Year
3,500
3,000
2,500
2,000
1,500
1,000
500
0
4
3
2
1
0
60 62 64 66 68 70 72 74 76 78 80 82 84 86 88

Fig. 2 Jamaican human population growth since Columbus and the depletion of local fisheries resources (from Jackson 1997). Fisheries became inadequate some time in the mid-19th century when the local population was about 15% of that today. Value for 1492 arbitrarily set at 100,000 which is almost certainly much too low (Sauer 1966). Sources for population size: 1658-1798 (Long 1774), 1844-1871 (Gardner 1809), 1901 (Duerden 1901), 1920-2000 (Hughes 1994), 1980 (National Geographic Society 1981).

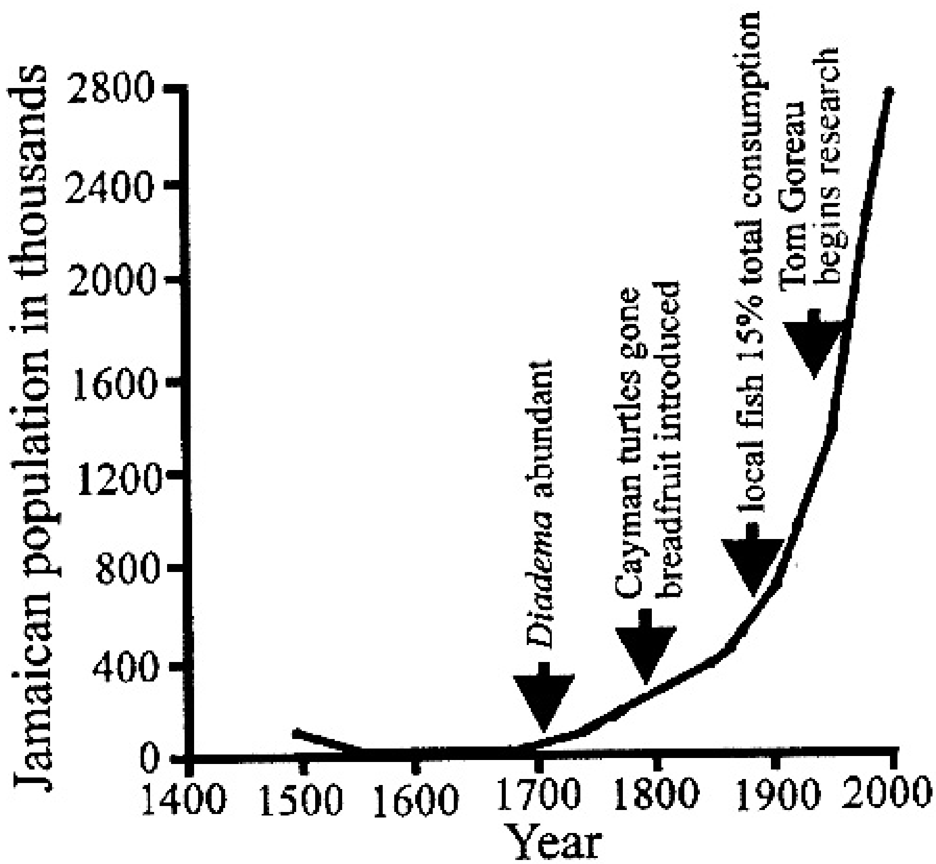

Fig. 3 Ordination of diatom assemblages from nineteen New England lakes. Line lengths represent the amount of change between the surface and bottom section of a 40 cm long sediment core. Lakes with twice the change of others in the same lake class could be considered unacceptable as a reference condition (Hughes 1995).

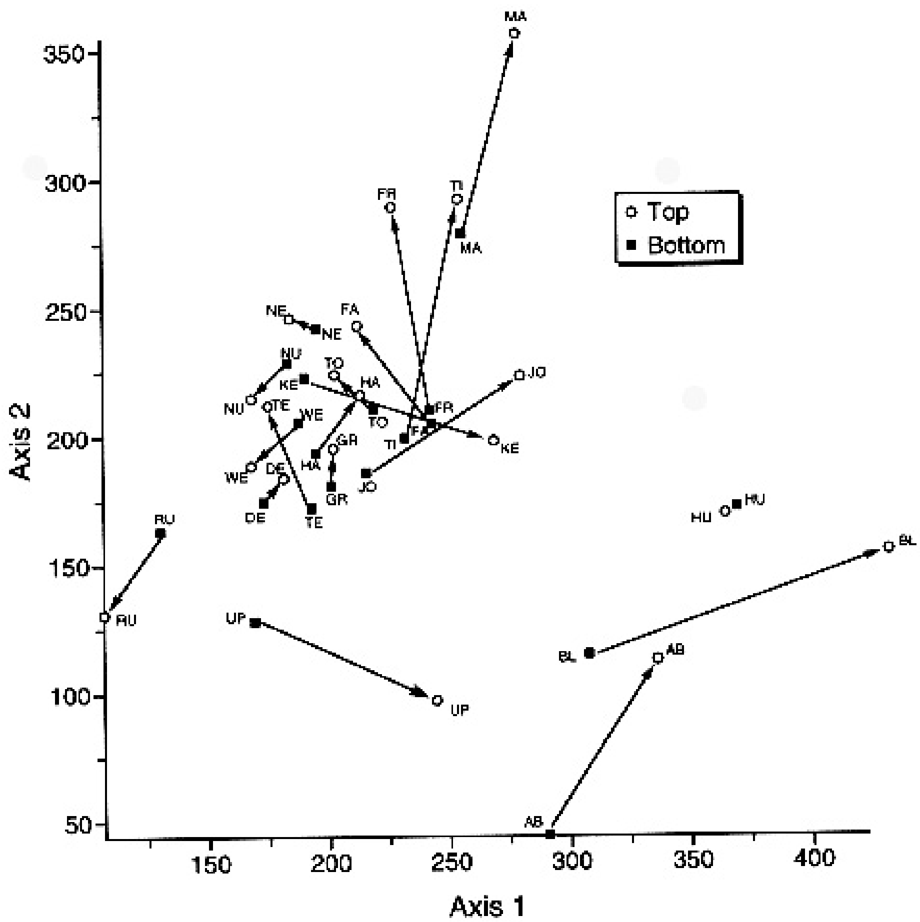

Fig. 4 Diatom-inferred nutrient enrichment of nineteen New England lakes. Lakes experiencing >10 g/l increase in total phosphorous could be considered unacceptable as reference conditions (Hughes 1995).

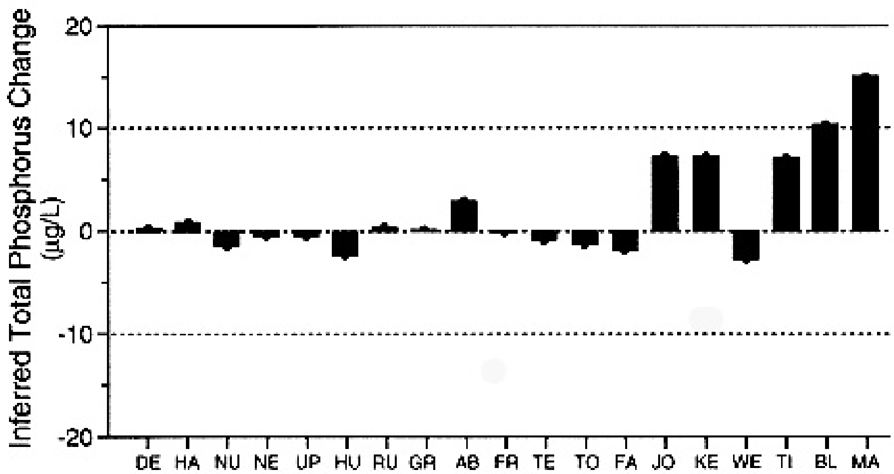

Fig. 5 A maximum fish species richness line. This line, or a 25 to 33% deviation from it, may be considered the reference condition. (Adapted from Fausch et al. 1984).

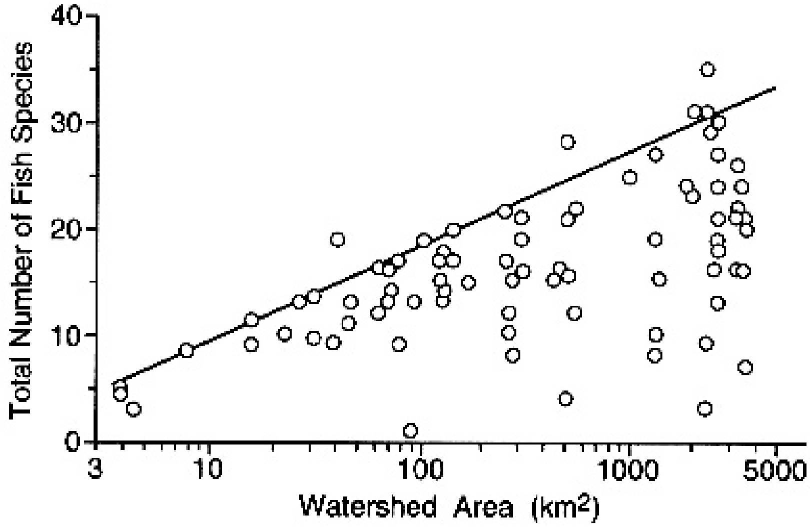

Fig. 6 Percent native fish species as a function of canopy complexity and extent, shoreline disturbance intensity, and fish cover complexity. A possible reference condition is 100% natives. (Adapted from Hughes et al. 1993).

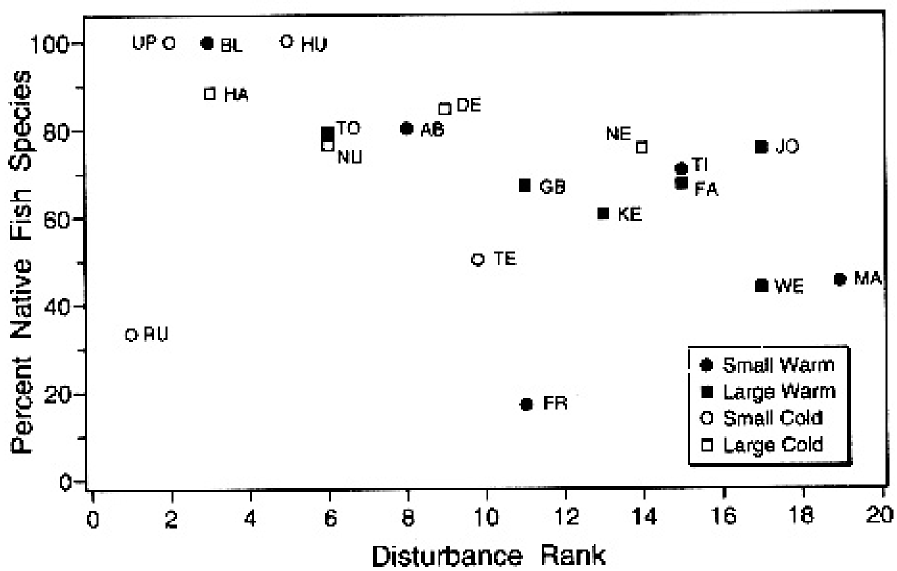

Table 1 Research priorities for creating a coral reef benthic macroinvertebrate index of biological integrity (IBI). Percent sign (%) denotes relative abundance (number of individuals of one taxa as compared to that of the whole assemblage). Cumulative = cumulative human-induced disturbance (i.e., a combination of factors that could include (but is not limited to) fishing, increased temperature and turbidity, chemical contaminants, sedimentation, altered flow regimes, pesticides, nutrients, metals, sediments, and/or bacteria. To reach metric status attributes need the following research: 1 = a quantitative dose-response change in attribute value documented and confirmed across a gradient of human influence that is reliable, interpretable and not swamped by natural variation; 2 = calibration for specific region/location; 3 = transformation. In addition, the entire IBI needs index development (an interpretive framework) that will result in the calculation of a simple numerical score for a particular site, which can then be compared over time or with other similar sites. Most attributes can be applied to all tropical seas, except those involving giant clams, which are not applicable to the Caribbean, South Atlantic and Gulf of Mexico (from Jameson et al. 2001).

Organizing structure attributes*	**Hypothetical response specificity**	**Hypothetical response**	**Research needs**
Community & Assemblage Structure			
Taxa richness			
Total taxa richness (number of taxa/sample)	Cumulative	Decrease	1, 2, 3
Total stomatopod taxa richness	Cumulative	Decrease	2, 3
Total amphipod taxa richness	Cumulative	Decrease	2, 3
Total decapod taxa richness	Cumulative	Decrease	1, 2, 3
Total gastropod taxa richness	Cumulative	Decrease	1, 2, 3
Total bivalve taxa richness	Cumulative	Decrease	1, 2, 3
Total polychaete taxa richness	Cumulative	Increase	1, 2, 3

Total oligochaete taxa richness	Cumulative	Increase	1, 2, 3
Total echinoid taxa richness	Cumulative	Decrease	1, 2, 3
Total holothurian taxa richness	Cumulative	Decrease	1, 2, 3
Total crinoid taxa richness	Cumulative	Decrease	1, 2, 3
Dominance/relative abundance			
% dominant taxa	Cumulative	Increase	1, 2, 3
% of bivalves that are bioeroding	Nutrients	Increase	1, 2, 3
Size frequency distribution			
Stomatopod modal size	Cumulative	Decrease	1, 2, 3
Taxonomic Composition			
Sensitivity (tolerants and intolerants)			
Number of intolerant taxa [1]	Cumulative	Decrease	1, 2, 3
% tolerant taxa [2]	Cumulative	Increase	1, 2, 3
Number of sediment-intolerant taxa [3]	Sediment	Decrease	1, 2, 3
% sediment-tolerant taxa [4]	Sediment	Increase	1, 2, 3
Rare or endangered key taxa			
Number of large gastropods	Fishing	Decrease	2, 3
Number of lobster	Fishing	Decrease	2, 3
Number of holothurians	Fishing	Decrease	2, 3
Individual Condition			
Anomalies			
Amphipod burrowing	Cumulative	Decrease	1, 2, 3
Gastropod imposex	Tributyltin	Increase	1, 2, 3
Giant clam zooxanthellae size	Nutrients	Decrease	2, 3
Foraminifera (Amphistegina) analysis of stress symptoms: mottling, lack of symbiotic algae	Nutrients	Increase	2, 3
Contaminant levels			
Nitrogen isotope ratios in tissues[5]	Sewage	Increase	1, 2, 3
Coprostanol concentrations[6]	Sewage	Increase	1, 2, 3
Bioaccumulation in bivalves	Metals	Increase	2, 3
Metabolic/growth rate			
Giant clam shell growth rate	Nutrients	Increase	2, 3
Mean weight per individual polychaete	Cumulative	Decrease	1, 2, 3
Mean weight per individual bivalve	Cumulative	Decrease	1, 2, 3

<u>Reproductive condition/fecundity</u>			
Fecundity[7]	Cumulative	Decrease	1, 2, 3
Biological Processes			
<u>Trophic dynamics</u>			
% predators	Cumulative	Decrease	1, 2, 3
% omnivores	Cumulative	Increase	1, 2, 3
% corallivores	Cumulative	Increase	1, 2, 3
% filter feeders	Nutrients	Increase	1, 2, 3
% deposit feeders	Cumulative	Increase	1, 2, 3
% autotrophic foraminifera	Nutrients	Decrease	1, 2, 3
<u>Settlement/recruitment rate</u>			
Recruitment rate[8]	Cumulative	Decrease	2, 3

[1, 3] potential candidates include: stomatopods, amphipods, decapods, gastropods
[2, 4] potential candidates include: heterotrophic macroinvertebrates (zoanthids, echinoids, holothurians, crinoids), polychaetes/oligochaetes, certain sea urchin species
[5, 6, 7, 8] potential candidates include: stomatopods, other reef crustaceans, giant clams, other molluscs.

* The organizing structure attributes are the framework for the definition of coral reef multimetric IBI's. They are rooted in sound ecological principles and a similar version has been successful in freshwater bio-assessment (Barbour et al. 1995). The use of each attribute is based on a hypothesis about the relationship between the coral reef condition and human influence. Multimetric indexes are generally dominated by metrics of taxa richness, because structural changes in aquatic systems, such as shifts among taxa, generally occur at lower levels of stress than do changes in ecosystem process (Karr and Chu, 1999). However, multimetric indexes also often include measures of ecological structure, frequency of diseased individuals, etc. and are broad in scope. Multimetric indexes can detect many influences in both time and space, reflecting changes in resident biological assemblages caused by single point sources, multiple point sources, and non-point sources. They can be useful in monitoring one coral reef or several, and they permit comparisons over a wide geographic area. The wide-ranging responsiveness of multimetric biological indexes makes them an ideal tool for judging the effectiveness of management decisions (Karr and Chu, 1999).

Table 2 Types of metrics, suggested number of metrics of each type, and corresponding levels in the biological hierarchy. Well-constructed multimetric indexes contain the suggested number of metrics from each type and therefore reflect multiple dimensions of biological systems (Karr and Chu, 1999).

Metric type	Number	Individual	Population	Community	Ecosystem	Seascape[1]
Taxa richness	3-5	X	X	X	X	
Tolerance-intolerance	2-3		X	X		
Trophic structure	2-4			X	X	X
Individual health	1-2	X				
Other ecological attributes	2-3	X	X	X	X	X

[1]Seascape is a geographical mosaic of different ecosystems. For example, the seascape at Christmas Island includes the fringing reef around the island, the reef flat between the fringing reef and the beach, and the inner lagoon with multiple habitat types, etc.

Table 3 Major steps in selecting coral reef reference sites.

Steps	Notes
1. Define areas of interest on charts or maps	Base area on natural not political boundaries. Delineate transition zones and areas that support markedly different assemblages.
2. Define coral reef classes of interest	Use criteria outlined in Jameson et al. (in ms.) to create coral reef classes (i.e., coral reef zones in specific biogeographic regions).
3. Delineate and evaluate watersheds and airsheds	Use maps, available data, remote sensing and regional experts. Evaluate land use, chemical use, pollutant discharges, hazardous waste sites, landfills, mines, oil fields, feedlots, poultry farms, fish hatcheries, atmospheric deposition, road proximity, livestock and human population densities, etc. Seek coral reefs near natural landscapes that are likely to endure (i.e., roadless areas, preserves). Reject disturbed sites and retain sites with minimal human influence.
4. Conduct aerial or photo evaluation	Used to help establish a regional perspective.
5. Conduct field reconnaissance	This is essential because map, chart and remote sensing data are often out-of-date or inaccurate and information from local experts may be inconsistent. An initial field assessment is useful to conduct through the use of a qualitative habitat evaluation form (Table 4).
6. Subjectively evaluate quality of candidate reference sites	Professional judgement tempered by extensive field experience are required. In most regions there may be trade-offs between accepting or rejecting higher levels of disturbance than desired, deciding the ideal level and type of coral reef classification, rejecting or accepting atypical sites, and locating a sufficient number of reference sites. The reasons for making such decisions should be documented.
7. Quantitatively evaluate biological condition of candidate reference sites	Survey several assemblages using coral reef IBI metrics (Jameson et al. 2001) at a number of sites that includes the full range of conditions and evaluate results to determine if some unknown stressor is acting on the systems.

Table 4 Qualitative checklist of observed human influences used to select reference sites. All characteristics indicate minimal human influence. Adapted from Hughes (1995).

Habitat Characteristic
___Human population centers distant
___Roads distant
___Mangrove extensive and old
___Shoreline modification minimal
___Chemical stressors (air and water) minimal
___Flow manipulation minimal
___Flushing rates high
___Sedimentation and turbidity minimal
___Odors, films, slicks minimal
___Pipes, drains, ditches absent
___Wildlife (terrestrial and marine) evident
___Human and livestock activity minimal
___Little or no history of coral bleaching
___Little or no history of coral disease

Table 5 Reference site candidates for coral reefs under United States jurisdiction. This is only a short list of high potential sites in United States waters. Other sites* may be appropriate and warrant investigation (including those outside of United States waters). Biogeographic region references from: [1]Sullivan Sealy and Bustamante (1999), [2]Ekman (1967).

Biogeographic Region / US Coral Reefs	Reference Site Candidates
Gulf of Mexico[1] / Flower Gardens	Flower Gardens National Marine Sanctuary
South Florida[1] / South Florida and Florida Keys	Tortugas Ecological Reserve
Central Caribbean[1] / Puerto Rico	Navassa Island
Lesser Antilles[1] / US Virgin Islands	Virgin Islands National Park (St. John)
Hawaii[2] / Hawaiian Islands	Northwest Hawaiian Islands Coral Reef Ecosystem Reserve
Central Pacific[2] / Wake Atoll, Johnston Atoll, Kingman Reef, Palmyra Atoll, Howland Island, Baker Island, Jarvis Island Central Pacific[2] / Marianas Islands - subregion Central Pacific[2] / American Samoa - subregion	Wake Island, Palmyra Atoll, Kingman Reef, Howland Island, Baker Island, Jarvis Island All Marianas Islands except Guam and Saipan (preferably the older southern islands of Rota, Aguijan, Tinian and Farallon de Medinilla with well-developed coral reefs) Fagatele Bay National Marine Sanctuary

* *Reference site alternatives:* Finding appropriate reference sites in Florida and the Caribbean will be challenging due to the proximity of coral reefs to large human populations which have already impacted coral reef systems (Jameson et al. 1995, Bryant et al. 1998, Jameson et al. 2002). While *coral* distribution, diversity and abundance may be different in the Tortugas Ecological Reserve than for coral reefs to the north, the ecological characteristics of non-coral IBI organisms might not be significantly different. The results of metric calibrations in these areas will ultimately resolve this issue. A possible non-US alternative reference site for Florida would be the Andros Island, Bahamas. An alternative for Puerto Rico would be Culebra Island, Puerto Rico. Metric calibration studies and best professional judgement will be critical in determining the utility of these alternatives.