Modeling Hawaiian coral reef "health"

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Abstract

A data base consisting of 61 variables measured at 184 stations within 52 sites in Hawai'i was used to develop and test statistical models of coral reef condition. Methods were restricted to rapid and inexpensive techniques. The Hydrogeomorphic Model (HGM) approach was used to classify the major habitats which were shown to be controlled primarily by wave energy and depth. A statistical analysis was used to select the key environmental factors and rank biological condition within each habitat. The use of "reference sites" was evaluated by developing a Reference Site Model (RSM). In addition, a completely objective Ecological Gradient Model (EGM) was developed based on quantitative ranking of each station. The RSM and the EGM both provide metrics ranked in a manner equivalent to the index of biotic integrity (IBI). Statistical analysis detected problems with the use of the RSM. The reference site approach often is used for paired site comparisons, but breaks down when multiple factors and multiple sites are involved. Nevertheless, the RSM can be used to detect severe degradation based on sediment, coral cover and fish abundance. The EGM describes reef condition in an objective and quantitative manner along a continuum. This model increases in power as more sites are evaluated and added to the data base. The EGM allows comparisons across a wide range of sites in relation to a standard based on the top percentiles. A link to specific types of disturbance may be determined from the rankings of these variables.

keywords: ecological model; coral reef; indicators; index of biotic integrity (IBI); reference sites

Introduction

There is a clear need for quantitative models or indicators that describe the general ecological condition or "health" of a coral reef community. For example, Federal Agencies conducted several recent workshops in Hawai'i in order to present their needs to the coral reef research community. Workshops were directed at promoting the development of techniques that can be used to establish impact of anthropogenic activity on coral reefs. The first was a joint Environmental Protection Agency (EPA), National Oceanographic and Atmospheric Administration (NOAA), U. S. Geologic Survey (USGS) Department of Interior (DOI) Workshop entitled "Assessing Pollution Stress on Coral Reefs" held at Waikiki Beach Marriott, Honolulu on 23-25 August 2004. A second workshop entitled "Coral Reef Functional Assessment Workshop" was held at the University of Hawai'i (UH) from 31 Aug to 2 Sept 2004 under the auspices of the U. S. Army Corps of Engineers (USACE) with participation by EPA, Hawai'i Department of

Health (DOH), NOAA, the Coastal Zone Management (CZM) and a wide range of research units. The most recent meeting entitled, “Coral Reef Biocriteria Workshop” was held at the NOAA Fisheries Pacific Island Regional Office on 22 Feb 2006 by EPA with the Division of Aquatic Resources (DAR), NOAA, DOH, and UH as participants.

Defining and measuring the condition of a complex coral reef ecosystem is an extremely difficult task. These communities are shaped by complex and highly variable interrelationships between numerous ecological factors. It is unlikely that the condition of a complex coral reef ecosystem can be described using measures of a single factor such as abundance of an “indicator species” or through measurements of a physiological process. However, there is a possibility that a series of key ecological metrics can be used to define the ecological status or “health” of a coral reef.

An extensive review of the coral reef ecosystem assessment literature concluded that “At this time, sufficient information does not exist to draft biocriteria guidance for coral reef ecosystems” (Jameson and others 1998). During 1998, the Hawai‘i Coral Reef Assessment and Monitoring Program (CRAMP) began an extensive field program in order to develop the techniques and compile the extensive data required to allow quantitative evaluation of the condition of Hawaiian coral reefs. The original CRAMP experimental design utilized a wide range of easily measured key variables. The program was designed to allow the eventual development of predictive models describing reef condition. Only inexpensive and rapid methods that are routinely used in coral reef monitoring and assessment were employed. The present investigation was directed at development of models that could be used to evaluate coral reef condition. The first step was to develop the required information in the form of a database. The second step was to quantitatively identify those factors that are reliable metrics for reef condition. The third step was to use these metrics to develop descriptive models. The fourth and final step was to test and evaluate the models.

Methods

1. Development of information database.

Methods used in this study were restricted to inexpensive and rapid survey techniques that are in wide general use by coral reef researchers and managers. Initial survey sites were selected by expert observers on the basis of degree of perceived environmental degradation, range of spatial gradients to encompass longitudinal differences, level of management protection and human population, and extent and direction of wave exposure. These sites represent an excellent cross section of Hawaiian coral reef communities (Figure 1).

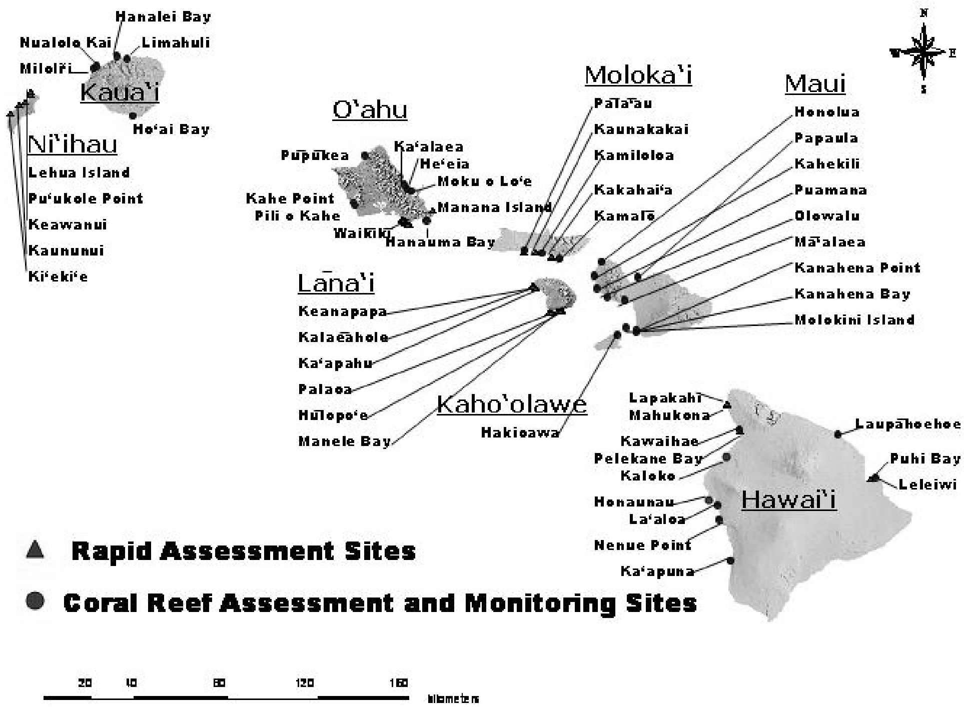

Figure 1. Main Hawaiian Islands assessment sites n=52.

Initial studies were conducted to develop an appropriate method for measuring benthic and fish communities (Friedlander and others 2003; Brown and others 2004).” At each site, digital benthic images along ten 10 m transects, fixed benthic photoquadrats, visual belt fish transects, substrate rugosity, and sediment samples were collected along with qualitative data.

Rugosity was measured using the chain and tape method (McCormick 1994). A light brass chain marked off in 1 m intervals was spooled out over the bottom along the entire length of each 10 m transect. The amount of chain necessary to span the distance between the two marker pins was divided by the straight line tape measurement to generate an index of rugosity for that transect.

Two replicate bulk sediment samples (approximately 500 cc each) were collected haphazardly within each study area and mixed to assure homogeneity. This mixture was divided into 4 sub-samples. Standard brass sieves with opening diameters of 500 µm, 250 µm, 63 µm and a brass catch pan were used to provide 4 sediment size fractions: coarse and very coarse sand, medium sand, fine and very fine sand, and silt and clay respectively in accordance with the Wentworth scale (Folk 1974). Two of the sediment sub-samples were wet sieved through the stacked sieves. All washings were collected and filtered to determine the silt fraction. The sediment fraction remaining on each sieve was washed through pre-weighed filter paper (Whatman Brand 114 wet-strength, 25 micrometer) and air-dried to constant weight. The percent weight of each grain size was determined by calculating the ratio of the various size fractions to the total sample weight.

To determine the inorganic/organic carbon fraction, 20 g of bulk sediment was ground with mortar and pestle to a fine, homogenous material and placed in pre-weighed crucibles. Subsamples were taken from each replicate to determine variability. These were placed in a drying oven at 100 ^{o}C for 10 h, cooled in a desiccator, and weighed. Next, the crucibles were placed in a muffle furnace at a temperature of 500 ^{o}C for 12 h, cooled in a desiccator, and re-weighed. Weight loss at 500 ^{o}C was assumed to be due to burning off of the organic fraction (Craft and others 1991). This analysis may over estimate absolute percentage values of organic material, so only relative differences were compared among sites for this parameter. The carbonate material was calculated by burning the samples in a muffle furnace for 2 h at 1000^{o}C (LOI_{1000}) followed by cooling in a desiccator and weighing (Craft and others 1991). The percent organic material and carbonate fraction was then calculated from these data.

Other ancillary variables included the following:

- Total human population within 5 km of each site and within the adjacent watershed was calculated using U.S. 2000 census data (www.census.gov/main/www/cen2000.html).
- Mean annual rainfall (mm), total acreage of the adjacent watershed, and perennial stream lengths were derived from layers obtained for each site from the State of Hawai‘i GIS website (www.state.hi.us/dbedt/gis).
- Mean, minimum and maximum values for offshore significant wave height (m) along with wave direction (compass bearing) were downloaded daily from the Naval Oceanographic WAM model website (http://www.navo.navy.mil) for 2001.
- Geologic age of the volcano underlying each site was estimated using data from Clague and Dalrymple (1994).
- Management status rank was included as a categorical predictor and pooled into 3 categories. A rank of 3 was assigned to Marine Protected Areas (MPAs) with the highest degree of protection (generally "no take" areas). Rank 2 included sites with a moderate degree of protection, for example restriction of certain fishing techniques such as gill netting and/or spearing or areas closed to taking of certain species. Rank 1 consisted of open access areas.

These data were entered into MS Access, MS Excel and ESRI ArcView as appropriate.

Analysis of the initial data (Friedlander and others 2003) indicated that a much larger spatial array of sites was desirable since the coral reefs of Hawai‘i are diverse and show high variability for many ecological parameters. Thus, the original data were supplemented using a rapid assessment technique (RAT). The RAT is an abbreviated version of the CRAMP monitoring protocol, using of a single 10m transect to describe fish communities, benthic cover, rugosity, and sediments. This protocol generates the same biological data (i.e. percent cover, species richness and diversity, fish abundances) and environmental data (e.g. rugosity, depth, sediments, etc.) as the CRAMP monitoring dataset. Multiple RAT transects were randomly selected using ARCVIEW spatial analyst. These transects were stratified on hard substrate habitats in a manner similar to the CRAMP monitoring sites but along a full range of depths. The advantage of the RAT is that it allows for the very rapid acquisition of data suitable to describe the variation in communities and the forces controlling these distributions in a spatial framework. The RAT is not designed to produce the type of data needed to detect temporal change such as gathered at the CRAMP monitoring stations. Only the first 10m CRAMP transect at each of the monitoring stations was included to allow for comparisons on the same measurement spatial scale (Transect area $3.5m^2$) with the RAT data. Twenty-two RAT sites supplemented the data from the 30 CRAMP permanent monitoring sites (Figure 1).

2. Identification of major factors.

To develop a model that includes attributes that respond to anthropogenic impacts, the environmental factors that most strongly influence biotic communities must be identified.

Data were transformed as appropriate to meet the assumptions of normality, linearity, and homogeneity of variance required for some of the formal statistical tests performed. Statistical analyses were conducted using Primer© 5.0, MVSP© 3.0, and Minitab© 13.0 software to examine both univariate and multivariate aspects of the spatial data sets. The database consists of 61 variables that were measured at 184 stations within 52 sites.

To identify which environmental factors were most important in structuring coral and fish assemblage characteristics and to narrow the field of variables, multiple regressions, correspondence analysis, and non-metric multi-dimensional scaling techniques were used. Multivariate procedures (BIOENV and SIMPER) were used to link biological data to environmental data to find patterns in coral communities and to determine the contribution of each species to site similarities. These results were later used in the development of the final model to determine weights for each factor.

3. Development of models.

Reference Site Model (RSM)

Most previous studies of coral reef condition have included reference sites. Thus, the initial modeling effort embraced this concept. In general, a “pristine” area is selected by experts to serve as a comparison to the “impacted” reef under study. Reference site selection can be troublesome due to the difficulty in determining optimal reef conditions. Sliding baselines that change over time can make determination of pristine conditions impractical. Without prior comparable historical data, this hypothetical baseline is elusive. A more pragmatic way to measure baseline conditions is to select sites unaffected by anthropogenic disturbances and compare their biological communities to other sites of interest. During the present study, sites remote from human influence or those in marine protected areas with a high degree of protection were qualitatively assumed to be reference areas. Reference sites must be determined qualitatively to avoid a circular argument where the quantified data is used both to select and analyze the sites. Although this provides an external means of defining the reference conditions used to compare against impacted areas, it is highly subjective.

Since depth and wave exposure were found to be highly influential in determining biotic communities, the first attempt at developing a model divided the reference sites into six habitat classes (3 depths and 2 wave exposures) based on these key factors. Considerable overlap between reference sites and non-reference sites prompted the expansion of the model to 12 habitat classes (3 depths and 4 wave exposures) based on depth and direction of wave exposure. The later factor is based on the work of Friedlander and others (2003) on fish communities.

Reference site analyses

Initially, it was essential to determine if the reference sites were environmentally different from the non-reference sites. A PCA was used to evaluate how well sites were separated (Figure 2).

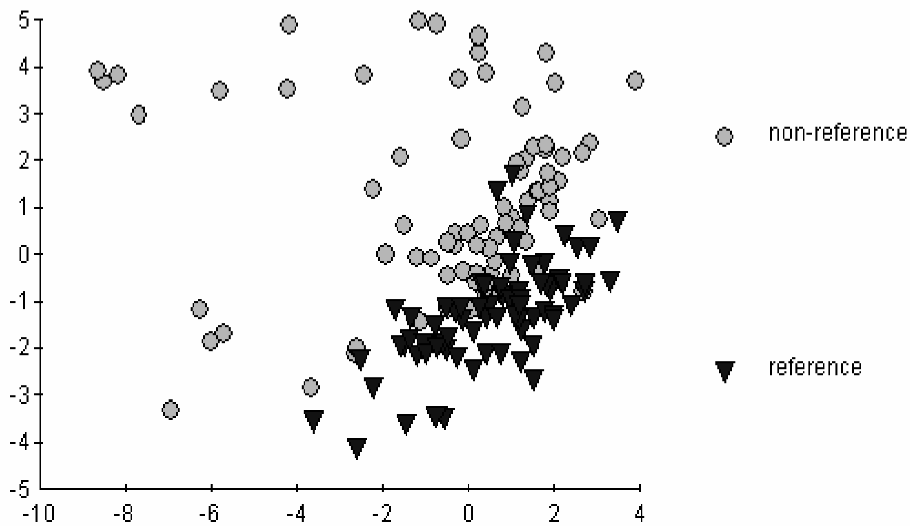

Figure 2. Principal components analysis of environmental variables of all sites (reference and non-reference sites) (n=184).

Next, it was necessary to determine if the reference sites in a given habitat class were different from the reference sites in other classes (Figure 3).

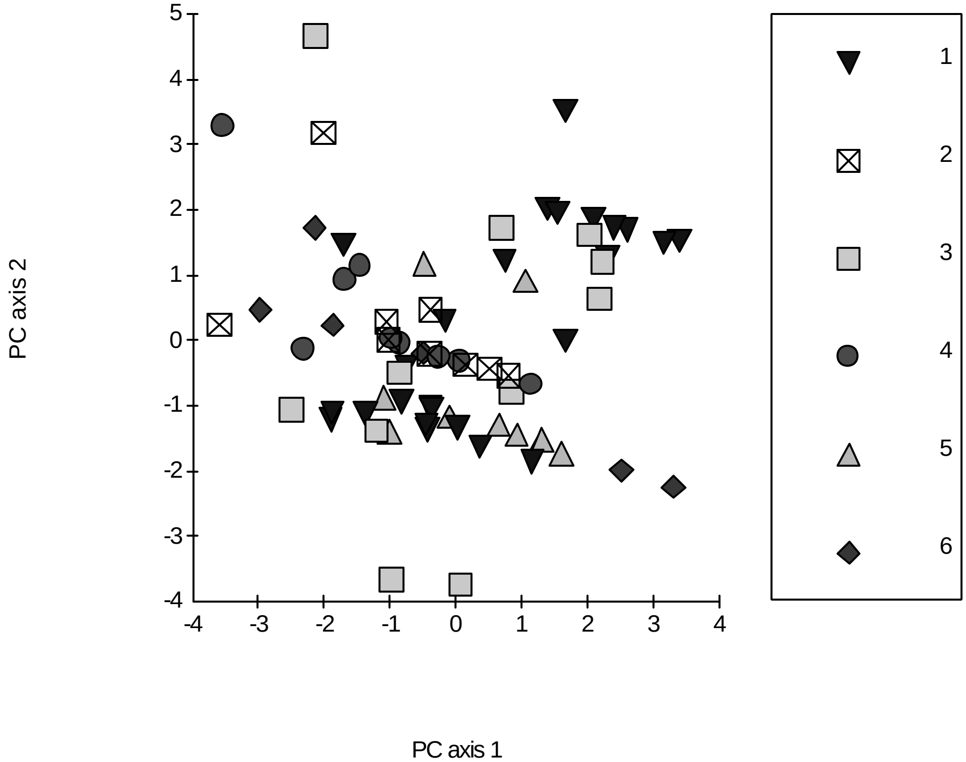

Figure 3. Principal components analysis of environmental variables of reference sites only by habitat class.

Several types of analyses were performed.

1) A discriminant analysis was performed to determine if the reference sites fell within their predicted habitat class.

2) A cluster analysis was also conducted to determine if the reference sites in each class grouped together.

3) An analysis of variance was used to determine which variables influenced these reference site similarities and which factors were significantly different between habitat classes.

Ecological Gradient Model (EGM)

Initial work showed that the reference site concept created difficulties because of its subjective nature so additional models were explored. A classification system based on depth, degree of wave shelter and wave regime, similar to the geomorphology and hydrodynamic characteristics used in the HGM approach, was implemented to define the major habitat classes (Brinson 1993; Brinson and others 1995; Brinson and Rheinhardt 1996; Magee 1996). Direction of wave exposure is based on work developed by Friedlander and others (2003) to evaluate the relationship of fish communities by their degree of wave exposure.

4. Evaluation and testing of models.

Reference Site Model (RSM)

It has been suggested that anthropogenic impacts may be established for a site if variables within a habitat class deviate from the established ranges of their reference sites (USACE Coral Reef Functional Assessment Workshop 2004). Two methods were employed in testing this concept.

1. Test sites.

Sites not previously surveyed were compared against reference values to identify departures from reference conditions within the appropriate habitat class and to evaluate the RSM's predictive ability to detect degradation. A site perceived to have high anthropogenic impact and a site with low disturbance were selected to test the RSM.

These two sites provided an additional 24 stations for use in model evaluation and testing.

2. RSM comparisons.

Non-reference sites with known impacts were compared against the reference ranges within the appropriate habitat class to determine if these values can indicate general disturbance and stress specificity. These sites were not used to develop the reference ranges, avoiding a circular argument. Sites were compared against reference standards to determine if the sites with evidence of impact could be detected by the RSM.

Ecological Gradient Model (EGM)

Since the values for most factors follow a continuum with high variability, all stations representing a gradient of degradation from severely impacted to unimpacted conditions were classified into one of twelve environmental groupings based on depth and wave exposure.

A model was created in Microsoft Excel© to identify where a quantified factor lies along a continuum of values. Forty-three physical and biological variables were included in the model. A statewide percent rank was generated for each site and for each variable of interest. In addition, an Index of Biotic Integrity (IBI) was generated for each site.

Results

Identification of major factors

Both natural and anthropogenic factors (rugosity, organics, depth, human population and wave regimes) are influential in structuring both coral and fish communities, explaining a considerable portion of the variability (Figure 4).

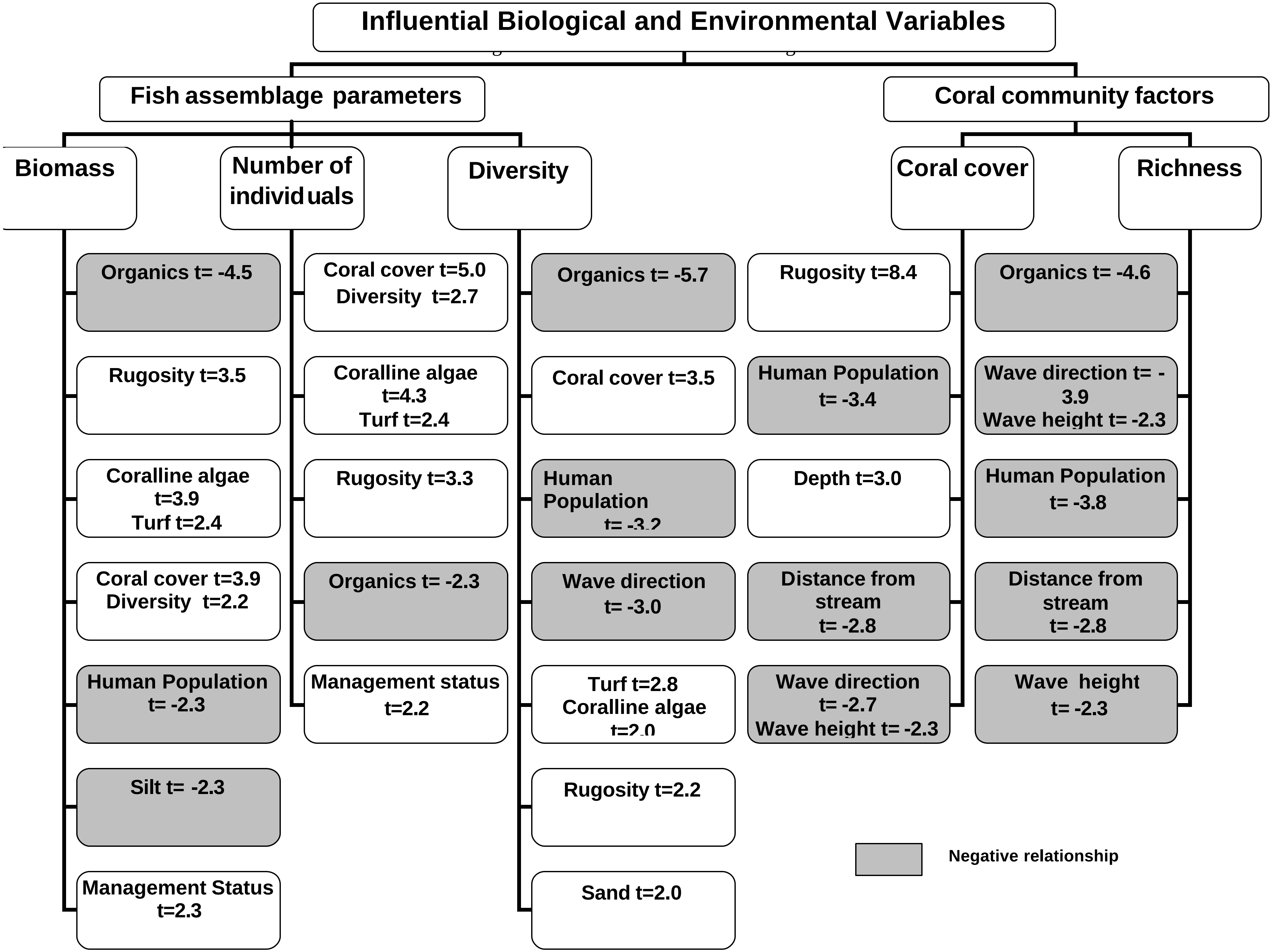
Influential Biological and Environmental Variables
Fish assemblage parameters
Coral community factors
Biomass
Number of individuals
Diversity
Coral cover
Richness
Organics t= -4.5
Rugosity t=3.5
Coralline algae t=3.9 Turf t=2.4
Coral cover t=3.9 Diversity t=2.2
Human Population t= -2.3
Silt t= -2.3
Management Status t=2.3
Coral cover t=5.0 Diversity t=2.7
Coralline algae t=4.3 Turf t=2.4
Rugosity t=3.3
Organics t= -2.3
Management status t=2.2
Organics t= -5.7
Coral cover t=3.5
Human Population t= -3.2
Wave direction t= -3.0
Turf t=2.8 Coralline algae t=2.0
Rugosity t=2.2
Sand t=2.0
Rugosity t=8.4
Human Population t= -3.4
Depth t=3.0
Distance from stream t= -2.8
Wave direction t= -2.7 Wave height t= -2.3
Organics t= -4.6
Wave direction t= -3.9 Wave height t= -2.3
Human Population t= -3.8
Distance from stream t= -2.8
Wave height t= -2.3
Negative relationship

Figure 4. Factors that significantly influence biological variables.

In addition, the distance from a stream is important to coral variables while fish communities are also influenced by silt, turf, coralline algae and management protection (Table 1).

Table 1 Summary of statistically significant (p<0.05) environmental variables for biological factors

	Coral cover		**Coral richness**		**Fish numerical abundance**		**Fish biomass**		**Habitat types**	
Environmental parameters	*t* ratio	*P*	*t* ratio	*P*	*t* ratio	*P*	*t* ratio	*P*	*t* ratio	*P*
Rugosity	8.4	<0.001	2.5	0.037	3.3	0.001	3.5	0.001		
Depth	3.0	0.003								
Silt/Clay							-2.3	0.023	2.5	0.04
LOI			-4.6	<0.001	-2.3	0.026	-4.5	<0.001		
Population	-3.4	0.001	-3.8	<0.001			-2.3	0.021		
Wave height mean	-2.3	0.023	-2.3	0.025						
Wave direction	2.7	0.009	3.9	<0.001					2.4	0.046
Stream distance	2.8	0.006	2.8	0.006						
Turf					2.4	0.020	2.4	0.016	3.2	0.011
Coralline algae					4.3	<0.001	3.9	<0.001	3.3	0.011
Large grain size									4.5	0.001
Sand									6.7	<0.001
Management status					2.2	0.033	2.3	0.022		

<u>Development of Models</u>

Reference Site Model (RSM)

Reference sites analyses

To determine whether the reference stations were different from the non-reference stations, a discriminant analysis was performed. 74% of the stations were correctly classified and 26% misclassified.

A Principal Components Analysis (PCA) was used to evaluate how well separated the undisturbed reference stations were from the disturbed non-reference stations. Although many of the reference stations (triangles) cluster together, others exhibit considerable overlap with the non-reference stations (circles) (Figure 2).

Since some degree of separation occurred between reference and non-reference sites, next it was critical to determine if the reference sites in each of the six habitat classes were different from one another based on biological and environmental factors.

To determine if the reference sites fell within the predicted classification a discriminant analysis was conducted. Of the reference sites, only 43% were in the predicted habitat class. Similar results were obtained when all stations were included (38%). Figure 3 shows considerable overlap of reference sites with no consistent pattern between the six habitat classes.

An Analysis of Variance determined most of the habitat classes were not statistically different from one another for the majority of the variables. Nine of the 61 variables showed distinct differences between at least two of the six habitat classes. The distinguishing factors include: sand ($F=6.9$, $p<0.001$), *Porites compressa* ($F=6.8$, $p<0.001$), very fine sand ($F=6.7$, $p<0.001$), medium grain-size ($F=4.5$, $p=0.001$), turf algae ($F=3.6$, $p=0.001$), calcareous algae ($F=2.9$, $p=0.001$), number of fishes ($F=2.6$, $p=0.03$), total coral cover ($F=2.5$, $p=0.04$) and silt ($F=2.5$ $p=0.04$).

Ecological Gradient Model (EGM)

It was demonstrated when identifying major influencing factors, that the composition of biological communities is partially controlled by the natural, physical factors of wave energy and depth which define broad ecological habitats. This result suggested an approach similar to the broad HGM classifications for the first tier, in which geomorphology and hydrodynamic characteristics (depth, degree of wave shelter, and wave regime) define the major habitat classes. Further, it is necessary to make reef condition comparisons only within each major habitat. For example, low coral coverage may be more indicative of wave regimes and depth than of deteriorated conditions since coral cover was statistically found to be significantly different between depths.

Habitat classification was expanded from six groups in the RSM to twelve groups in the EGM due to the increase in sample size. The RSM uses only reference sites, while the EGM takes advantage of the entire suite of sites. For the first tier, coastal sites were separated into groups based on major wave regime (North Pacific Swell or South Pacific Swell), degree of exposure (exposed or sheltered) and three depth categories (shallow <5 m, mid-depth 5 - 10 m and deep >10 m). This classification results in 12 major habitats.

Metrics for classification within the second tier include 30 biotic measures to define “biological integrity” and 13 environmental measures to identify signs of anthropogenic stress.

<u>Evaluation and Testing of Models</u>

Reference Site Model

1) Test sites

The two test sites selected represent the two ends of the spectrum, from minimally to severely impaired. Kaloko/Honokohau, Hawai‘i is under federal management protection (National Parks Service) and has relatively low anthropogenic influence, while Maunalua Bay, O‘ahu has open access and is perceived as impaired. Variable ranking determined that only three factors (coral cover, number of fishes, and silt/clay) have ranges that are narrow enough to describe site condition. The ranges of these factors within their respective habitat classifications were used to compare with the two test sites. These values were expected to fall within the reference range for their respective classification for Kaloko/Honokohau and below reference ranges for Maunalua Bay. As expected, all stations (17) at Kaloko/Honokohau exhibited values within the reference ranges, while the majority of the stations (71%) were below reference ranges at Maunalua Bay.

2. RSM comparisons.

Previously surveyed non-reference sites with evidence of environmental impact were also compared to the range of reference values within each habitat class to test the validity of the model. The same variables used for the test sites were used to compare impacted sites. Comparisons indicate that the majority of stations at Waikiki have values for numerical fish density and coral cover that are outside the reference ranges for each station’s habitat class. Coral cover is below reference levels for their respective habitat class for all 11 transects, while the number of fishes is below reference values at over half of the stations. This concurs with the established impacts from overuse and identifies the specific area within the site where disturbance is occurring. In concordance with the lack of impact by sedimentation at the stations surveyed, silt values at Waikiki stations, where bulk sediment samples were collected, are within the reference ranges.

When comparing reference ranges to 99 stations at 26 non-reference sites, the silt/clay fraction is well above the upper range of values for sites predicted to have sedimentation impacts. The sites with established disturbance of sedimentation that far exceed the reference values include: Kakahai’a, Kamiloloa and Pala‘au, Moloka‘i, Hakioawa, Kaho‘olawe, Pelekane Bay, Hawai‘i, and Kane‘ohe Bay, O‘ahu. Sites that have silt values slightly higher than reference levels include Puamana Maui, Laupahoehoe, Hawai‘i and Kamalo, Moloka‘i. This is in agreement with the US EPA’s list of polluted coastal waters showing evidence of degradation by sediments, nutrients, or bacteria. This list, revised in 2002, is based on all available water quality data. The majority of listed sites are near streams with a high level of adjacent urban and agricultural activities. Of the nine sites that fell outside reference ranges, seven are on the EPA list. The sites detected by the reference model but missing from the EPA list are Hakioawa, Kaho‘olawe and Laupahoehoe, Hawai’i. The island of Kaho‘olawe is not listed in the polluted coastal waters list, but the reefs have been subject to extreme degradation due to siltation. The Laupahoehoe site receives runoff from a large watershed and is subject to extremely high wave energy from persistent NE Trade Wind waves. This site requires further investigation.

Sites outside reference ranges for fish abundance

In addition to Waikiki, numerical fish densities are well below reference levels at the majority of stations in Pelekane Bay, Hawai‘i and Kamiloloa, Moloka‘i, and at deeper sites in Kane‘ohe Bay. One station on the shallow reef flat in Hanalei Bay, Kaua‘i is also outside the lower reference range of values. This is in concert with Friedlander and Parrish (1998) who found the lowest biomass to occur on the reef flats, compared to other substrate types within Hanalei Bay. All five sites are included in the EPA polluted coastal waters list.

Sites outside reference ranges for coral cover

Since exposed habitats may have little or no coral cover, the reference values for these sites are meaningless, thus only sheltered sites were considered. Eight sheltered sites are outside the lower reference range. These sites where the majority of transects have low coral cover, Leleiwi, Puhi and Pelekane Bays, Hawai‘i, Kamiloloa, Moloka‘i, Waikiki and Kane’ohe Bay, O‘ahu and Ma‘alaea and Puamana, Maui are documented to have current or historical anthropogenic impacts that affect coral coverage. All eight sites are on the EPA polluted coastal waters list.

Ecological Gradient Model (EGM)

The major forcing functions on coral reef communities were found to be from both natural and anthropogenic sources (Figure 4). Depth, wave regimes, human population, spatial complexity, organic sediment and fine grain size explain a considerable portion of the variability in coral and fish assemblage characteristics. Results from the identification of these key factors were used in the development of the EGM. The EGM recognizes that all ecological factors vary over space and time. It is designed to establish reef condition through comparison to the same habitat class in a large number of other Hawaiian reefs in a completely objective manner using a wide range of factors that may be linked to specific types of disturbance. All stations, representing a gradient of degradation from severely impaired to unimpaired conditions are classified into one of twelve environmental groupings based on depth and wave exposure. A total of 43 physical and biological variables were included in the model encompassing variables on a species, population, community, and ecosystem level (Table 2).

Table 2. Physical and biological variables incorporated in the ecological gradient model

Physical Factors		**Biological Factors**		
Other variables	**Sediment variables**	**Coral Assemblage Characteristics**	**Fish Assemblage Characteristics**	**Algal Characteristics**
Rugosity	Composition Organics $CaCO_3$	Total coral cover	Abundance Numerical Biomass Diversity Evenness	Macroalgae Calcareous Turf
Substrate type (sand, silt)	Grain-sizes Medium sand Fine sand Very fine sand Silt/clay	Species *Porites lobata* *P. compressa* *Montipora capitata* *M. patula* *M. flabellata* *Pocillopora meandrina*	Trophic guild Corallivores Detritivores Herbivores Mobile Inverts Sessile Inverts Planktivores Zooplanktivores	
Human population w/in 5km w/in 10km Watershed		Species richness	Size classes <5 cm 5-15 cm >15 cm	
Precipitation Distance from stream		Species diversity	Endemism status Endemic Indigenous Introduced	

This model, intended as a management tool, was created in Microsoft Excel© to evaluate site condition. The operator enters a depth, wave exposure and an assessment value for a single factor or a group of factors into the worksheet. A statewide percentile for a particular variable of interest is calculated to evaluate that variable relative to all others in a particular class. For example, the fish biomass at Hanauma Bay is in the100th percentile of all sheltered reefs 5- 10 m affected by south swells.

In addition to the rank percentile, an overall site IBI is calculated based on the number of variables input by comparing all other sites in that classification. This IBI is based on a scale of 0 to 10, where zero represents the most impaired site and ten corresponds to the least impaired site. Each individual factor is weighted (CRAMP IBI) based on an objective multivariate analysis of the primary factors defining reef condition. However, the option is also provided that allows the operator to change the weights to suit a particular management or ecological question or leave all factors unweighted. For example, one might wish to create an index that assigns the greatest weight to fish biomass, with little weight assigned to other factors. An IBI relevant to the question is thereby calculated, and a ranking of sites produced.

Discussion

Reference Site Model (RSM)

The RSM can sufficiently detect sites that strongly deviate from reference values for select factors in sheltered regions. While it is able to detect values that fall outside the reference ranges at highly impaired sites, it is not able to detect marginal degradation because of high variability within reference sites. The RSM based on classification of reference sites and the use of reference values to detect degradation is effective for use in the evaluation of levels of sedimentation. However, ranges suggest that only severely degraded conditions of coral and fishes for specific habitat classes can be detected. Possible degradation can be detected by values of coral cover outside the lower reference ranges at sites with sheltered wave regimes, but not in exposed regions that typically exhibit low coral cover. Furthermore, only strong deviations of numerical fish abundance can be detected, due to high variability. Other influential factors can not be evaluated with this model. The RSM's applicability on a broad scale is evidenced by the agreement with the EPA "most impaired site" listing. Both listings are somewhat subjective with the EPA listing determined largely by water quality and the RSM being determined mainly by ecological conditions other than the EPA criteria.

Results of this investigation show the limitations of using a "reference site" or a "control reef" in determining "reef health" or reef condition.

- The reference sites standard cannot distinguish degree of impairment. The extremes of "severely impaired" and "little or no impact" can be defined, but the high variability in range restricts the ability of reference ranges to discriminate on a finer scale.
- Reference site values have limited power in detecting disturbance. High variability among most variables prevents identification of specific causes of disturbance. Natural heterogeneity increases reference ranges and decreases the ability of reference sites to detect impaired reef condition. For example, high wave energy environments naturally have extremely low and variable coral cover values that are not related to anthropogenic factors.
- A small sample of reference sites cannot accurately describe the range of biological integrity encountered among reef communities. There is high spatial and temporal variability that cannot be encompassed by a single reference site or a small number of reference sites. When attempting to integrate a large number of reference sites, conditions can overlap substantially with non-reference sites (Figure 2).

- Subjective selection of reference sites even by experts is flawed. No two reefs are exactly alike in all respects, so agreement on appropriateness of any "control" or "reference" reef cannot be attained in an absolute sense and may be biased and inaccurate. Quantitative analysis showed poor separation between reference and non-reference sites. Determination of optimal reef conditions is obscured by the lack of knowledge of the anthropogenic history of a site and sliding baselines that change over time. The reference concept is defective largely because it does not embrace the diversity of unimpacted reef communities.
- When comparison is made against reference sites in the evaluation of impairment, contrast of non-reference sites with other non-reference sites is unattainable.

The reference site paradigm was not found to be applicable in the Hawaiian marine environment because of the complexity and extreme heterogeneity of coral reef ecosystems. The reference site standard cannot encompass the spatial variability and temporal fluctuations found in the reefs of the MHI.

Ecological Gradient Model (EGM)

Many factors combine to influence coral reef communities, but most explain a very small portion of the variability. Both natural factors (rugosity, depth and wave energy) and anthropogenic factors (organics, human population, management protection and distance from a stream) influence biotic assemblage characteristics (Figure 4). Although these factors are the most influential in explaining the observed variability in coral community structure, many other factors combine to varying degrees to influence biological populations.

Stratification of marine organisms is principally influenced by depth, spatial complexity, and wave regimes. This pattern is analogous to terrestrial botanical zonation, which is primarily based on elevation, topography and rainfall. These oceanic, geologic, and meteorological differences created diverse habitats, supporting varied biotic distributions and abundances making selection of reference sites difficult. Unlike the attributes used to create the index of biotic integrity for freshwater systems, most marine attributes are not comprised of distinct ranges, but instead follow continuous gradients. (e.g. coral cover can range anywhere from 0 to nearly 100%).

Multiple variables that have an influence on the biological communities follow overlapping and often dissimilar continuous gradients that confound defining of boundaries. Thus, it is advantageous to use a large number of sites within each habitat classification and rank the sites along a continuum by purely objective criteria. In this way the condition of the reef can be defined in comparison to a wide range of other reefs within its habitat classification. The method continues to grow in power as the number of sites, parameters and classifications are increased.

This approach provides metrics that can be ranked in relative value to form an index of biotic integrity. A low ranking can assist management in identifying degraded areas that may need further investigation or monitoring. A high ranking can identify sites that may be suitable for protection as marine protected areas (MPA). Comparing rankings can aid in assessing compatibility of experimental and control sites for use in manipulative field experimentation. A link to specific types of disturbance may be highlighted in these rankings. For example, a high ranking of silt/clay and organics can be indicative of areas heavily impacted by sedimentation.

Data from resurvey of these sites can be used with this model to compare against baseline data to estimate impact of major environmental events such as storm waves, bleaching events or local anthropogenic disturbances such as sedimentation or eutrophication. These data can be used to test the effectiveness of each parameter in predicting coral resistance and recovery. Such results can be utilized in strengthening the MPA selection process, evaluating existing management protocol, and designing future monitoring programs.

We must incorporate joint scientific and management efforts in order to protect and preserve our marine resources. Modeling coral reef health through identification and evaluation of marine inventory that separate natural from anthropogenic impacts can be valuable in detecting biological condition and comparing reefs.

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