Long Term Coral Reef Monitoring Programs: Working Towards a Synthesis of Science, Management, and Policy

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Statement of the Issue

CORAL reefs are complex ecosystems threatened globally with a variety of natural and anthropogenic factors. Scientific monitoring is the primary source of information on reef biology and status. However, monitoring is both a scientific endeavor and a decision-making management tool. As a result, this dual nature leads to controversy and there is considerable debate among scientists about the design and methodology of these programs. Thus, although monitoring programs are often focused on important biological questions, they may have weak links to management and environmental policy. These links need to be strengthened for effective management and intervention.

This paper is a synthesis of presentations and discussions that took place both during and after the 9th ICRS, and included scientists, reef managers and policy-makers. Several major coral reef monitoring programs in the Atlantic, Caribbean, and Pacific, and their relationship to management and policy issues at both the local and national levels, were reviewed.

Photo: Brian Tissot

Monitoring in Mahikona, Hawaii

State of Knowledge

Careful Design, Integration and Cooperation are Important

Although monitoring questions are often based on simple scientific principles and methods, it is a challenge to distinguish natural from human-induced variation. Careful attention to the types of data collected, including indicator species such as benthic algae and temporal patterns in the distribution and abundance of recent and old dead coral, can provide important information on population dynamics.

Monitoring programs require a substantial amount of energy to be established and maintained, and there are institutional barriers to establishing long-term programs. Monitoring is undervalued in comparison to experimental science, and it is difficult to sustain funding over the time scales needed to detect meaningful change. Moreover, holistic approaches that integrate both the causes and effects of human impacts on reefs often require interdisciplinary cooperation, which clash with traditional disciplinary boundaries and funding sources.

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Formulate Realistic Targets
Another important issue is the statistical rigor of monitoring programs. To be efficient, monitoring programs need to be focused on specific testable hypotheses or questions. However, question-driven programs are based on specified experimental designs that require specific target levels of accuracy and statistical error rates. Due to substantial (and non-linear) trade-offs between accuracy and effort, formulating realistic target levels is critical to program design and success. Unfortunately, many monitoring programs are not based on the needs of reef managers and may be overly accurate and thus inefficient with limited financial resources. Statistical rigor can also be increased by using paired control-impact designs, habitat-based stratified approaches and by methods that increase replication or reduce measurement error.

Role of New Technologies
One of the most important long-term drivers of monitoring programs is likely to be changes in technology. Thus, research exploring new methodology is important and rigorous monitoring programs should be adaptive to new methods as they emerge. Increases in the resolution of remote sensing combined with increasing scales of underwater survey work are beginning to provide large-scale data for ecosystem management. However, efficient management at the ecosystem level will require better integration of state and federal policy and cooperation and collaboration among a wide variety of stakeholders.

Relevant Actions Being Taken and Management/Policy Implications

There is a strong need for scientists and resource managers to collaborate when developing and implementing long-term monitoring programs. Reef managers need to develop the specific questions and criteria they need to be effective managers and scientists need to link their experimental designs to these questions. Moreover, policy makers need to use language detailing specific terms and/or outcomes from programs that link science and management issues together. A good example of this type of monitoring program is the West Hawaii Aquarium Project (WHAP). WHAP is run by a consortia of academic scientists working with Hawaii resource managers and biologists to measure the effectiveness of marine reserves created to evaluate the policy-mandated "effectiveness" of the reserves to increase the productivity of an aquarium fishery. WHAP is cost-efficient because it uses highly-trained undergraduate students generated from the QUEST coral reef monitoring workshop to conduct reef surveys (see references).

There is also a need to develop a question-driven decision tree. That is, given a specific management question what monitoring programs and methods are good models. The development of this tool would help facilitate collaboration between scientists and managers and reduce the amount of controversy around methodological and statistical issues. The decision-tree should also include a framework for integrating ecological concepts (for example, disturbance) with the appropriate methodology so there is consistency both within and among programs.

The creation of a question-driven decision tree can be facilitated by developing standards through a national and/or international coral reef monitoring program that all programs could build on and provide a central clearinghouse for data, metadata and survey methodology. Good examples of international monitoring programs exist in the GCRMN/Reef Check model and the ReefBase database. At the National level the USA Coral Reef Conservation Act offers an opportunity to mesh state and federal policy and establish a national coral reef monitoring program. However, to develop an efficient, effective and sustainable monitoring program there is a need to conduct a comprehensive review and synthesis of existing long-term programs and identify gaps in information and methodology.

Specific Recommendations for Action

- Monitoring programs need to be designed with strong links to reef management issues;
- Reef managers need to develop specific questions and criteria and collaborate with scientists;
- Policy should address realistic and measurable scientific/management questions;
- A question-driven decision tree needs to be developed to guide the experimental design of monitoring programs;
- Research on new survey methodology should be ongoing and monitoring programs should be flexible and incorporate new methods;
- There needs to be greater coordination among monitoring programs at the national and international levels and the development of a central clearinghouse for data and methodology.

Useful References and Resources:

This paper was prepared from presentations and discussions at the 9th International Coral Reef Symposium, with special emphasis on Mini-Symposium D2 "*Central Questions, Experimental Design, and Methods of Long Term Monitoring Programs: A Synthesis of Ecological Concepts and Data*." Authors and titles of presentations can be found at: www.nova.edu/ocean/9icrs/

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The West Hawaii Aquarium Project Web site: (www.coralreefnetwork.com/kona/)

Coral Reef Biodiversity: Assessment and Conservation

Sheila A. McKenna [1] and Gerald A. Allen [2]

Statement of Issue

WITH limited resources and the increasing degradation of coral reef ecosystems, finding an effective and methodical way to prioritize coral reef areas for conservation is critical. The loss of biodiversity is one of the worst problems. Its most severe and irreversible outcome is species extinction, and often a coral reef area is lost before the rich diversity of organisms living there is properly documented. The establishment of marine protected areas is one means of preserving coral reefs, and their location needs to take into account the biodiversity, overall reef condition, and threats. Coral reefs targeted for conservation should ideally capture the most representative and richest sites to maximize biodiversity conservation impact. Given the immense biodiversity on coral reefs, it is impossible to document all taxa.

An alternative approach is to inventory key indicator groups along with other variables such as endemism, threat, habitat diversity and socio-economic issues. Further, an understanding of the variability in patterns of marine biodiversity is needed. This baseline information is critical for realistic and effective conservation activities. Managers and policy makers need to know what parameter(s) and indicators of reef biodiversity are being used and studied to assess and identify reef areas for conservation, and to make informed and effective conservation decisions. This summary from the 9th ICRS reviews indicators that are used to assess coral reef biodiversity, patterns of marine biodiversity that have been elucidated, and priority areas for reef conservation that have been identified. Case studies of areas in which assessments were made are also provided.

Photo: Gerald R. Allen

Pseudochromis – a new species found on Conservation International's Marine RAP Expedition of Raja Ampat Islands, Indonesia

State of Knowledge

Corals as Indicators of Reef Diversity

An analysis of global patterns of coral diversity at three taxonomic levels (family, genus and species) revealed that patterns of reef coral diversity become defined and more detailed as one progresses from the family to the species level. For example, beginning at the genus level, a well-defined Indo-Pacific center of diversity emerges in the Indonesia-Philippines region that is not evident at the family level. Patterns within this center of diversity are apparent at the species level. Reasons for this progression in coral diversity pattern with taxonomic level are partly attributed to continental drift and mass extinctions at the family level, closure of the Tethys Sea and the Central American Seaway at the generic level, and ocean currents and changing climates at the species level.

Molluscs as Indicators of Reef Diversity

An analysis of 1268 species of molluscs in 10 regions of the tropical Indo-West Pacific found the greatest diversity to occur in the Indo-Australian Archipelago ("coral triangle") with a total of 321 endemic species. Molluscan diversity and endemism is a useful tool for helping to establish the location for survey efforts for coral reef conservation studies.

In addition to diversity and endemism, an increase in understanding of phylogenetic relationships of highly diverse taxa also provides important data for consideration in developing conservation strategies. Results of

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phylogenetic studies of many clades of opisthobranch gastropods on Indo-Pacific coral reefs suggest that the Indo-Pacific represents a historically significant evolutionary and biogeographic unit. An examination of giant clams found the nine extant species to be restricted to the Indo-West Pacific with the West Pacific as the center of diversity. Alarmingly, some species have become depleted and locally extinct in the Indo-Pacific, and rearing and re-introductions are taking place as part of current management practices.

Coral Reef Fishes as Indicators of Reef Diversity
Coral reef fishes are another fauna commonly used as key indicators of diversity to identify conservation priority sites or "hotspots." A zoogeographic analysis involving 2051 species of fish revealed 35 sites of local endemism and regional patterns (Figure 1). The highest endemism was found in the Hawaiian Islands. Additional data analysis revealed a detailed pattern of reef fish diversity in the Indo-Pacific with its center occurring in the Indonesia-Philippines region. Results suggest that this area may be the highest priority for coral reef conservation based on its extremely rich biodiversity, significant endemism, and extensive habitat degradation.

Case Studies on Coral Reef Assessments
In Guam, an intensive survey of the marine fauna suggests that the fauna of even well-studied areas can remain poorly known and that small islands can host several tens of thousands of species. Reef assessments in the Sulawesi Sea, Indonesia, and the northern Saudi Arabian Red Sea used a combination of indicator species and other factors such as diversity and function of habitat, as well as socio-economic data, to identify priority regions for conservation through the establishment of marine protected areas. Within the Atlantic Ocean, the reefs of Brazil were identified as an area for conservation priority due to the small reef area, significant endemism and high risk of habitat loss, due primarily to the high human population and deforestation along the coast.

A global analysis of reef regions for conservation priority was presented. This "equal area grid" analysis involved a map-based approach to show global distribution of species richness and endemism of fish, cone shells, and lobsters. The level of risk from a suite of human threats was calculated for each area, using the "Reefs at Risk" data base from the World Resource Institute. Focusing on regions rich in restricted-range species may be valuable in conserving species. However, the central question is whether to establish conservation projects in target areas under less risk where the probability for success will be greater, or in target areas under severe risk from threats.

Relevant Actions Being Taken to Address the Issue

Developing criteria to set conservation priorities on coral reefs is a relatively new approach and is proving to be a complex issue. No one criterion or set of criteria can be

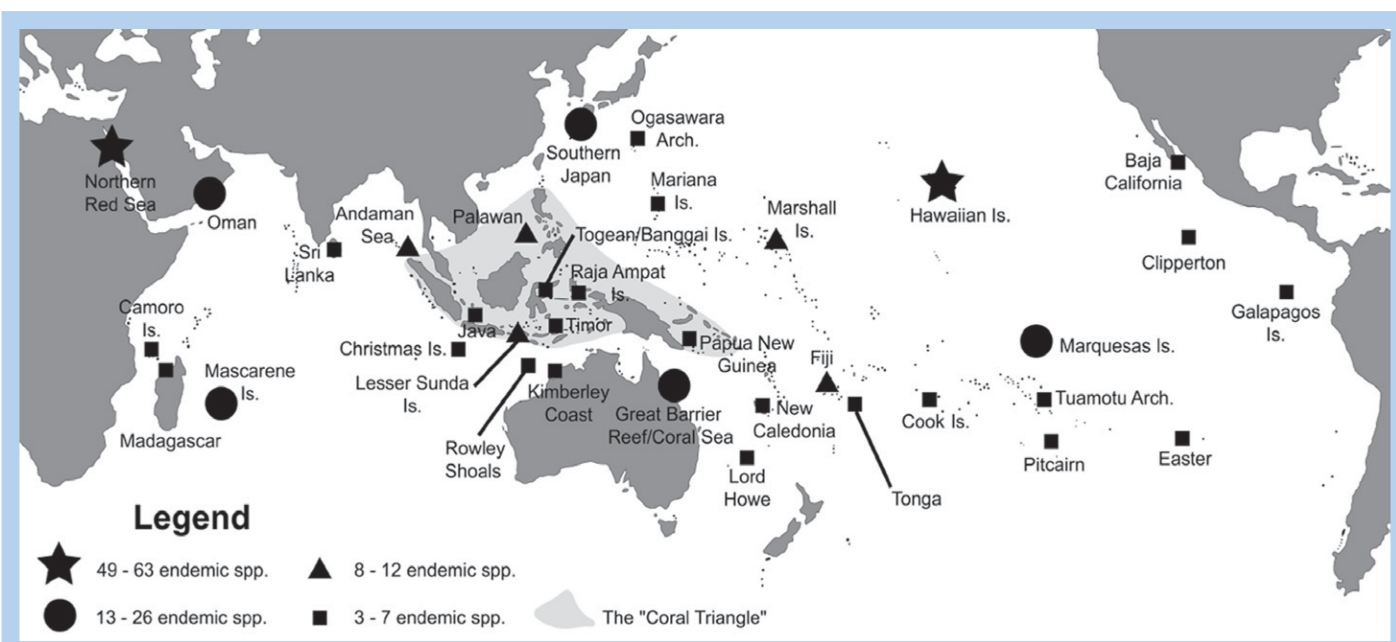

Figure 1. **Hotspots for reef fish endemism in the tropical Indo-Pacific. The "coral triangle" is indicated by shading.**

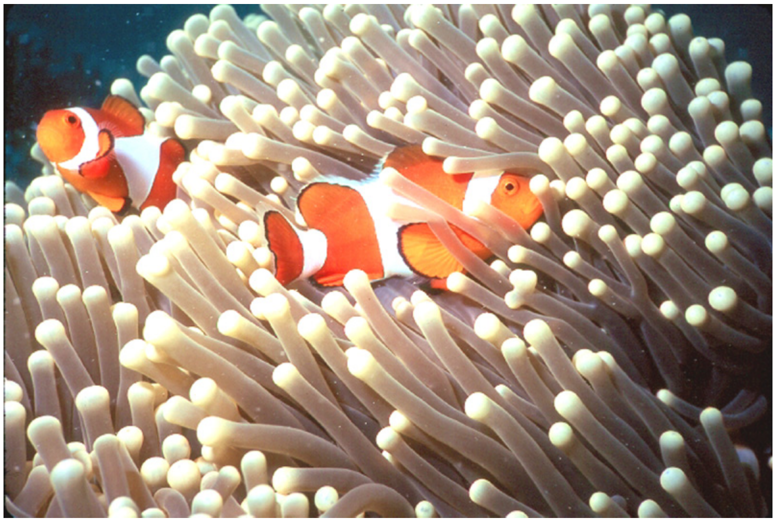

Photo: Steve Turek

Portrait of two orange, black, and white Clownfish (*Amphiron ocellaris*) inside their host – Magnificent Anemone (*Heteractis magnifica*), Malaysia

labeled right or wrong. Coral reef researchers are constantly fine-tuning the methodology and analyzing the data to prioritize reefs for conservation. Gaps in our knowledge of biodiversity and other data such as functional groups and habitat diversity on previously unsurveyed reef regions are gradually being filled. Additional scientific tools are being applied in combination with biodiversity data to aid the process of priority-setting on reefs (e.g. phylogenetic analysis and geology).

Management and Policy Implications

Coral reefs targeted for conservation should ideally capture the most representative and richest sites to maximize biodiversity conservation impact. Managers and policy makers need to know the importance of biodiversity, its patterns, and the various criteria used to prioritize reef areas for conservation. They need to have access to well-designed reef survey assessment reports for effective conservation decisions and activities. This knowledge is imperative to ensure that managers and policy makers set aside reef areas that include the best representation of biodiversity.

Specific Recommendations for Action

- Reduce sources of anthropogenic impacts on reefs, especially those that decrease habitat quality or lead to loss of habitat and loss of species diversity.
- Continue research on the variability of marine biodiversity patterns at multiple scales and on the use of new tools to assess coral reefs for conservation merit.
- Continue research on factors affecting marine biodiversity such as resiliency to disturbance, population viability and persistence.
- Continue studies on previously un-surveyed reef regions to document biodiversity and other criteria for conservation.
- Consider socio-economic issues in tandem with biological data in regions identified for reef conservation efforts, so that realistic activities are implemented to preserve coral reefs.
- Educate all stakeholders (policy makers, managers, local community) on the importance of marine biodiversity.
- Unify efforts to preserve reef diversity among governments, non-governmental organizations, universities, and stakeholders.

Useful References and Resources

This paper was prepared from presentations at the 9th International Coral Reef Symposium, Mini-Symposium D3 *Coral Reef Biodiversity: Assessment and Conservation.* Authors and titles of presentations can be found at: www.nova.edu/ocean/9icrs/

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Monitoring and Assessment of Coral Reefs: Studies from Around the World

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Statement of Issue

SCIENTIFIC advances in monitoring and assessment that were presented at the 9th ICRS were divided into four main categories: benthic monitoring techniques; population ecology studies; reef fish monitoring; and pollutants, anthropogenic impacts, and community studies. Many researchers demonstrated new and innovative techniques for gathering data and/or used multiple methods to address monitoring and assessment challenges. These advances highlight the usefulness and application of new techniques, as well as the need for addressing information gaps to improve the early warning and diagnostic capabilities of coral reef monitoring and assessment.

Photo: Rob Waara

Diver using a sonar positioning system and video camera to record transect data in the U.S. Virgin Islands

State of Knowledge

Benthic monitoring techniques

In a resource assessment off the northwest coast of Australia, a variety of rapid broad-scale methods were used to produce estimates of marine resources, describe the ecology and structure of reefs and shoals, map seabed types, and measure the size and extent of recent mortality of hard corals. Methods used in shallow habitats included visual transects, fish visual census and remote sensing. On the shoals, video camera transects, acoustics, and sediment grabs were used. Geographic information systems (GIS) were used for designing stratified sample strategies, data analysis and reporting.

A method involving video-camera transects and a sonar positioning system was used to monitor reefs in the U.S. Virgin Islands. Revisiting the same transects produced better statistical power and ability to document change than sampling different transects each time.

To address the change in substrate components from a depth gradient of 10-250 meters in the Bahamas, a method of repeated photographic techniques was used over a three-year period. Results showed that a complex interplay of abiotic and biotic disturbance forces, diminishing light levels, and changing phyletic dominance, accompanied by shifting tradeoffs in competitive abilities, occurs along the bathymetric gradient.

To quantify sexual and asexual recruitment within populations of mushroom corals exposed to chronic sedimentation stress and acute cyclone disturbance, a multi-method approach was used that included size frequency distributions, tagging and recapture of polyps, and genetic analysis. A true indication of population dynamics was obtained only when all three methods were combined, thus illustrating the importance of combining methods and the care required when extrapolating conclusions from limited data.

To gather data on the primary production of reefs around NOAA's underwater Aquarius laboratory off Key Largo, Florida, a newly developed coral respirometer was used. Experiments also provided information on ways to improve the design of the respirometer.

Population ecology of various taxa

One study compared the growth rates of tagged green sea turtles from two reef systems in northwestern Australia. Results showed that age at maturity may differ by decades

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depending on locality, and that population and harvest models produced for some areas are not applicable to all populations.

The use of a video recorder (CRITTERCAM) can be used to explore new aspects of feeding behavior in animals. For example, a video recorder mounted on the backs of endangered Hawaiian monk seals in the French Frigate Shoals, Hawaii, was used to test the hypothesis that seals frequent deep-water coral beds to feed on associated fish assemblages and improve their overall foraging success.

Monitoring in the U.S. Virgin Islands found a wide variation in the settlement density of western Atlantic spiny lobsters, and linked sand substrate with high settlement density. A successful mark-recapture program for *Nautilus pompilius* was developed for use at Osprey Reef, an isolated reef in the Coral Sea off Queensland, Australia. The size, sex, and age structure of the population was characterized for comparison with less isolated populations. The usefulness of public aquaria for research on reef fish behavior was also demonstrated; public aquaria can also be used to increase our ecological understanding of other reef species.

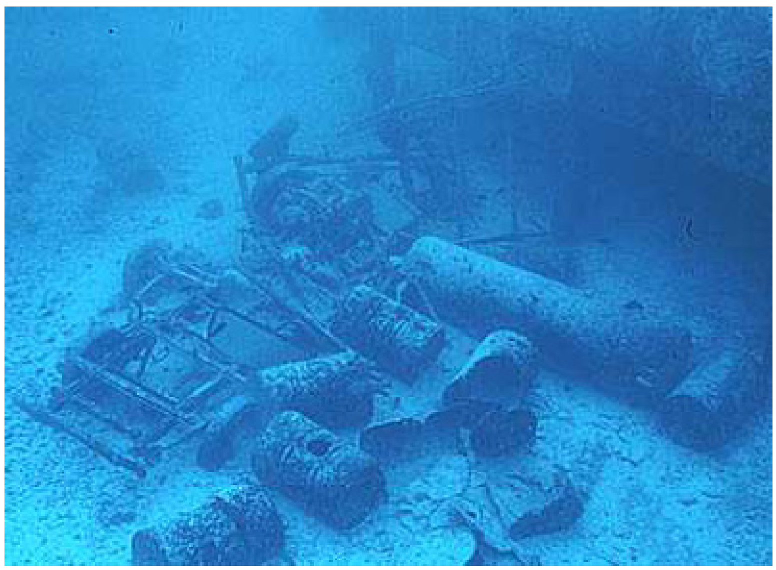

Photo: Phillip S. Lobel

Discarded fuel containers, 55 gallon drums, and other debris found in the nearshore marine environment around Sand Island, Johnston Atoll

Reef fish monitoring

Using underwater footage in a television and video demonstration, species-specific courtship and mating sounds were used to monitor reproduction in reef fish populations. This application can be used as an alternative or supplement to traditionally more destructive and labor intensive methods.

Data collected by Reef Environmental Education Foundation volunteers were shown to be useful in the Florida Keys National Marine Sanctuary to identify species-rich sites as potential management priorities. A collation of butterflyfish diversity and abundance on over 1000 reefs from the Red Sea to the northern Great Barrier Reef was used to suggest that the total number of butterflyfish per transect may be a useful universal indicator of reef quality. A multivariate technique was used to identify reef morphology, exposure, and coral bleaching as major forcing factors in reef fish community structure in the southwestern Philippines.

Visual surveys of reef fish in the northwestern Hawaiian Islands were conducted with particular focus on conservation of the Hawaiian monk seal and its prey. Five times and 15 times greater densities for lizardfishes and moray eels, respectively, were found at Midway Atoll versus French Frigate Shoals. A fivefold less frequent encounter of large jacks was found at Midway Atoll compared to French Frigate Shoals.

Pollutants, anthropogenic impacts, and community studies

An assessment of the status of contaminants in sediments and biota at Johnston Atoll after 70 years of military operations, found the greatest concentrations of contaminants located nearest sites on the islands where hazardous materials were used. One difficulty of assessing the Johnston Atoll sediment data is the lack of comparative measurements from similar but minimally-impaired tropical atolls. Subsequent surveys will provide data to evaluate whether contaminant concentrations remain stable or are attenuating through dispersal. In general, the pattern of contaminant distribution in fishes matches that found in sediments. The occurrence of abnormal demersal damselfish and triggerfish embryos (sensitive indicators of anthropogenic perturbations) was significantly higher at PCB contaminated sites for both species. This technique may allow comparisons at the scale of the home range or territory of species.

In one broad-geographic study, seagrass biomass showed varying patterns from 1993-1999 with some stations increasing by a factor of two (Jamaica), decreasing precipitously (Bermuda), maintaining a value with little variation (Mexico), and showing wide variation about a mean (Belize). C:N:P ratios of the *Thalassia* leaves were determined to estimate localized nutrient excesses and deficiencies. In the Hiddaduwa Marine Reserve, Sri Lanka, a year-long study provided rare data showing that *Halimeda* in the reef lagoon serves as a refuge habitat and nursery ground for a wide variety of marine organisms.

Management and Policy Implications

Many researchers demonstrated new, efficient, economical, and innovative techniques for gathering data and/or used multiple methods to address management challenges. From sonar positioning systems for divers, to video recorders strapped to the backs of monk seals, the innovations and multifaceted approaches exemplify the creativity in the coral reef scientific community. This creativity needs to be supported and encouraged. It is only through this innovation that coral reef managers and decision makers will be supplied with the timely information they need to make critical coastal management decisions.

Methodology and experimental design is another important theme with management and policy implications. Scientists must understand the strengths and weaknesses of their methods and explain these to decision makers – whether it is the statistical power benefits derived from re-sampling permanent transects versus a randomized approach, the need to use multiple methods to fully understand recruitment within coral populations, or the importance of proper monitoring methods to design population and regulatory models for sea turtles. Without understanding these methodological strengths, and especially weaknesses, the information that scientists provide could be biased and/or incomplete and could have serious resource management consequences.

Finally, if we are to move beyond traditional non-diagnostic monitoring techniques (where we monitor change but can not really explain what is causing the change) and towards diagnostic techniques with early warning capabilities, we must explore new coral reef attributes, develop dose response curves for them across a gradient of human influence, and formulate these metrics into indexes. Several researchers presented work in this direction, such as using fish embryos to detect the impacts of PCB's, using C:N:P ratios of *Thalassia* leaves to estimate localized nutrient excesses and deficiencies, and developing an underwater coral respirometer. This work is critical to the future monitoring, assessment and management of coral reef resources around the world.


Photo: Lisa M. Kerr

Normal and abnormal *A. sordidus* embryos. The abnormal embryo on the right displays severe craniofacial and cardiac deformities

Specific Recommendations for Action

This was a mini-symposium with presentations on many diverse subjects and themes. While specific recommendations for action on each subject or theme would be too lengthy for this synthesis, we would like to highlight one recommendation for future action that cross-cuts all categories.

The United States Environmental Protection Agency is exploring the feasibility of developing multimetric indexes of biological integrity (IBIs) for coral reef assessment. Information presented at this mini-symposium along with future targeted monitoring and assessment information will help fill the information gaps necessary to move this new effort forward. This work presents a research strategy for creating coral reef IBI's that outlines the specific areas that need further investigation.

The approach of using IBIs for coral reef assessment is unique with respect to traditional coral reef monitoring and assessment in the following ways:

- Coral reefs are classified so comparisons between similar environments can be made.
- Minimally impaired reference conditions are developed and used to compare against monitoring sites.

- Coral reef IBIs only use metrics that show a quantitative dose-response change in attribute value, that is documented and confirmed across a gradient of human influence that is reliable, interpretable and not swamped by natural variation.
- IBIs are designed to provide a unique early warning and diagnostic capability.
- Well constructed IBIs typically examine two or more assemblages because different organism groups react differently to perturbation. The more diverse the measures used, the more robust the investigative techniques and the more confidence the manager can place in the results.
- This idea must be reconciled with the limitations of the costs of multiple and diverse surveys and the relative availability of reliable scientific methods to measure some assemblages. The most promising IBI approaches will likely be measures of sessile epibenthos, benthic macroinvertebrates, fish, macrophytes, phytoplankton, and zooplankton.

Useful References and Resources

This paper was prepared from presentations at the 9th International Coral Reef Symposium, Mini-Symposium D6 *Monitoring and Assessment of Coral Reefs: Studies from Around the World.* Authors and titles of presentations can be found at: www.nova.edu/ocean/9icrs/

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Jameson SC, Erdmann MV, Karr JR, Potts KW (subm a) "Classifying coral reefs for diagnostic monitoring and assessment: A framework for estimating biological similarity among sites." *Coral Reefs*

Jameson SC, Erdmann MV, Karr JR, Potts KW (subm b) "Establishing reference conditions for the diagnostic monitoring and assessment of coral reefs." *Atoll Research Bulletin*

For more details and progress reports on the development of coral reef indexes of biotic integrity, please visit: www.epa.gov/owow/oceans/coral

For a summary of how IBIs are used in freshwater environments see: Karr JR and Chu EW (1999). *Restoring life in running waters: better biological monitoring.* Island Press, Washington, DC. 206 pp.