Priorities for Caribbean Coral Reef Research

Results from an International Workshop of the
National Center for Caribbean Coral Reef Research (NCORE)

October 3–5, 2001

Miami, Florida

Edited by: John W. McManus

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Workshop Organizers

NCORE
National Center for Caribbean Coral Reef Research

National Center for Caribbean Coral Reef Research

U.S. Environmental Protection Agency

Khaled bin Sultan
Living Oceans Foundation

International SeaKeepers Society

Rosenstiel School of Marine and Atmospheric Sciences

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Executive Summary

Background

The coral reefs of the Caribbean and Western Atlantic are vital to the economies of regional nations, and to the maintenance of livelihoods of millions of reef-dependent people. They represent the highest known biodiversity in these seas, and supply a substantial portion of the fisheries harvest of the region. Over the last two decades, degradation and disease have become rampant. Most alarmingly, many of these reefs have increasingly lost their resilience following damage from disruptions such as hurricanes. Pollution, overfishing, and other stresses seem to increasingly favor the growth of seaweed over that of corals following disturbances. These and other key processes are poorly understood, and this paucity of knowledge seriously hampers management action to conserve and properly manage coral reefs.

Coral reefs are highly complex ecosystems, often heavily influenced by even more complex socioeconomic and political systems. Policy and decision-making, such as on the deployment of marine protected areas, the regulation of coastal development and the implementation of fishery regulations, usually cover scales of hundreds to thousands of kilometers for time periods of 4 to 10 years. They generally involve the integration of a wide range of interlinked considerations based on limited biophysical and socioeconomic information balanced against strong political forces. Science in support of these decisions is often conducted on much smaller scales of time and space, and is often highly specialized, with results difficult to rationalize against those of other disciplines. Much of what science does have to offer does not reach the decision process, and that which does is often not specifically applicable to the decision being made. This weakens the role of science in decision-making and reduces the availability of funding for science, thus perpetuating the inadequate scientific basis for coral reef management.

It is crucial that this cycle be broken. In this era of rapid advances in science and technology, current efforts to understand coral reef ecosystems and their management are lagging far behind what is possible. Today's investments in the research necessary to keep these ecosystems operating would, if they were corporations, be considered irrationally small.

If we are to improve the situation, then we must develop a more organized assault on the unknown. We must develop biophysical-socioeconomic studies at scales of time and space that are relevant to management and sufficient to account for natural processes. We must support these projects with studies of coral disease, improvements in remote sensing analyses and other key efforts within-disciplines. In all cases, we must involve the best scientists to maximal capacity in cross-institutional teams, while at the same time building up the scientific capacities of regional nations. In the absence of large pools of available funds, some larger projects can be supported through collaboration based on smaller resources obtained by individual scientists. As results become increasingly useful to policy makers and managers, then perhaps more reasonable and reliable funding support will become available. This workshop represents a key step in this process.

The Workshop

On October 3–5, 2001, sixty-five experts from 11 countries met in Miami, Florida, to identify priority areas for research in support of the management of coral reefs. The participants were individually chosen so as to represent a broad range of scientific and management fields, a variety of institutions, and a reasonable coverage of the region. Following a morning of general presentations, five key experts gave summary presentations on the four main topics of the workshop:

1. Scientific Needs for Integrated Coastal Management —Janet Gibson
2. Coral Reef Mapping and Remote Sensing —Peter Mumby

3. Coral Reef Health and Connectivity
—Eric Jordan Dahlgren
4. Bleaching and Diseases of Coral Reef Organisms
—Peter Glynn and Ernesto Weil

This was followed by a full day of parallel breakout sessions in the above groups. The following morning, rapporteurs Alessandra Vanzella Khouri, Serge Andréfouet, Robbie Smith and Shawn McLaughlin respectively presented plenary summaries of discussions from the four working groups for inputs from the group as a whole. A summary of the workshop was presented by co-chair Jorge Cortés. Subsequently, workshop chair John McManus compiled the notes from the meeting. These were made available for comment by the group and the general public via email and the Internet.

The priorities are intended to facilitate providing regional scientific support for the:

- International Coral Reef Initiative
http://www.icriforum.org/ (ICRI)
- International Coral Reef Action Network
http://www.icran.org/ (ICRAN)
- Global Coral Reef Action Network
http://www.gcrmn.org/ (GCRMN)
- International Coral Reef Information Network
http://www.icriforum.org/ (ICRIN)
- ReefBase
http://www.reefbase.org/
- Atlantic and Gulf Rapid Reef Assessment
http://coral.aoml.noaa.gov/agra/index.html (AGRRA)
- Caribbean Coastal Marine Productivity Program
http://isis.uwimona.edu.jm/centres/cms/cm00006.htm (CARICOMP)
- Caribbean Reefs at Risk Project
http://www.wri.org/
- MesoAmerican Barrier Reef Project
http://www.inweh.unu.edu/biology447/modules/intro/mbrp.htm,
- U.S. Coral Reef Task Force
http://coralreef.gov/ and its member agencies

and other international, national, state and local efforts to improve coral reef management. They address and support actions identified in connection with:

- Agenda 21
http://www.unep.org/unep/partners/un/unced/agenda21.htm
- the Convention on Biological Diversity
http://www.biodiv.org/
- the Caribbean Environment Programme
http://www.icriforum.org/ext_disp.cfm?Uval=http://www.cep.uneo.org, and
- the ICRI Framework for Action
http://coral.aoml.noaa.gov/icri/icri.html.

The workshop was organized by the:

- National Center for Caribbean Coral Reef Research http://www.ncoremiami.org/ (NCORE) of the Rosenstiel School of Marine and Atmospheric Sciences http://www.rsmas.miami.edu/ of the University of Miami http://www.miami.edu/.

It was co-hosted by the:

- Khaled bin Sultan Living Oceans Foundation
http://www.khaled-livingoceans.org/
- International SeaKeepers Society
http://www.seakeepers.org/

Core sponsorship was provided by the:

- U.S. Environmental Protection Agency
http://www.epa.gov/ (EPA) and supplemented via the above partnerships.

Priorities for Caribbean Coral Reef Research

Summary of Results

The results of the workshop reinforce the conclusions of the more general review of environmental science and engineering of the National Science Foundation (NSF), published in February, 2000*. Specifically, both this workshop and the NSF review call for:

1. More reasonable and predictable funding and resources.
2. Highly integrated cross-institutional, interdisciplinary socioeconomic-biophysical research.
3. Focused research within key disciplines.
4. Long-term research.
5. Environmental education.
6. Research on the methods and models used in environmental assessments, funding prioritization, and studies of the effectiveness of actions to address environmental issues.
7. Improving infrastructure for environmental observations, data handling, and networking.
8. Improvements in supportive technologies.

Thus, the priorities described below are consistent with those of the NSF study, and identify specific areas in which the latter recommendations can be addressed most effectively for coral reefs.

Recommendations by Topic

In the sections that follow, the order of presentation does not reflect levels of importance.

Scientific Needs for Integrated Coastal Management and Fisheries

1. *There is a need for a better understanding of the relationships between human activities and the processes involved in reef ecosystem function.*

Recommendations:

Focus studies on how the ecosystem responds to natural and anthropogenic influences given a variety of impacts occurring at various frequencies. Conduct biophysical—socioeconomic research on the recovery and restoration of reefs under conditions of pollution and extractive uses. Further develop forensic and retrospective analysis of reef disturbances. Determine the direct and indirect impacts of tourism on reefs. Include the human dimension in long-term ecological research and baseline studies. Investigate the effectiveness of various performance criteria for coral reef management systems. Analyze the effectiveness of NGOs vs. government institutions in various roles within integrated coastal zone management. Expand research efforts into the quality of life of reef dependent people, and use this to develop more effective means to assess the potential impacts of management interventions on the reefs and associated human communities.

2. *There is insufficient biophysical and socioeconomic knowledge for effective reef fisheries management.*

Recommendations:

Conduct research on stock structure and population connectivity, and on the effectiveness and design of marine protected areas (MPAs) in relationship to fisheries. Support experimental and manipulative research for fisheries management using multidisciplinary (socioeconomic and biophysical) teams of researchers. Improve and implement methods to determine yield capacities of coral reefs. Elucidate the relationships between quality of life and fishing. Develop analytical and management approaches that will help to guide fisheries policy to improve economic and gender equity and favor fishery access by low-income coastal dwellers. Investigate options to reduce fishing pressure through alternative livelihood programs and access limitations. Determine factors that influence compliance with fishery regulations, such as participation in decision-making, and develop strategies to improve compliance. Conduct research on the effectiveness of improving fisheries management via various

* NSF 2000. Environmental Science and Engineering for the 21st Century: The Role of the National Science Foundation. National Science Board (NSB 00–22). <http://www.nsf.gov/cgi-bin/getpub?nsb0022>.

types of marketing and advocacy campaigns, an through certification and eco-labeling.

3. *The implementation of improved policies is inhibited by inadequacies in our capacity to conduct economic valuations and to assess damages.*

Recommendations:

Develop alternative techniques for valuation and damage assessment applicable to local and regional scales, to include cost-benefit approaches, values for non-market uses, consumptive vs. non-consumptive uses and the use of proxy values for short-term analytical requirements. Integrate damage assessment with interdisciplinary predictive spatial coral reef modeling to ensure that the full socioeconomic and biophysical costs of the damage over time are accounted for.

4. *There is a lack of user-friendly, accurate and appropriate methods and models to facilitate integrated coastal management.*

Recommendations:

Develop queriable and user-friendly decision-support systems, according to scale, including relevant layers of information on ecological, socioeconomic, legal and policy issues, incorporating a participatory approach for planning and information gathering at the lowest scale of governance. Combine these systems with predictive interdisciplinary spatial models developed in conjunction with fieldwork for mapping, parameterization, calibration and validation. Conduct training in the use of these systems. Support regional and national scale analyses of coral reef status, including the upcoming Caribbean Reefs at Risk Anaylsis, and ensure that the results of such studies and the data on which they are based are widely and freely available.

5. *A lack of direct communication and awareness at all levels often results in well-established scientific principles not being effectively implemented.*

Recommendations:

Implement a multifaceted effort to incorporate current knowledge into policy-making. This can include translating, effectively packaging and positioning guidelines at key policy and decision-making levels, developing interpersonal linkages between scientists and policy makers, making effective use of the media and of a variety of public forums, and developing information stores linked to dissemination networks. Conduct research on the effectiveness of education campaigns, and on determining the best means to apply existing knowledge to effective management. Strengthen institutional capacity for management and science throughout the region. Involve economists, lawyers, behavioral scientists, policy-makers and managers in meetings on environmental matters. Educate and involve local economists and lawyers in environmental investigations. Conduct behavioral research on ways to improve enforcement and self-management at the local community scale.

6. *There is insufficient knowledge on human carrying capacity and its relationship to sustainable development and land-use.*

Recommendations:

Conduct socioeconomic-biophysical research on the determination of human carrying capacity in a variety of coastal situations at local and regional scales. Develop simple techniques to conduct these determinations using 'footprint' analyses aimed at determining impacts per individual and institution, and employing graphical analysis and presentation.

Remote Sensing and Mapping

7. *Coral reef management and science is hindered by the fact that most coral reef communities have never been adequately mapped, and in many cases, their locations are not known.*

Recommendations:

Develop a meta-database of existing maps and related data for the coral reefs and coastal watersheds of the Caribbean, and initiate an organized effort to map the rest to satellite levels of resolution and depths of penetration. Organize efforts to map reefs below 10 meters via modern ship-borne acoustic methods. Identify areas where management or scientific objectives require more detailed investigation, and conduct detailed mapping using combinations of airborne laser depth-finding (LIDAR) and hyperspectral (finely divided light bands) data. Make all products readily available over the Internet, with fully disclosed data on accuracy, history and format. Actively involve recreational divers and monitoring programs in ground-truthing remotely sensed data. Building on geographic information systems, combine high-resolution depth data with maps of ecological communities, with hydrographic, ecological and socioeconomic models, and with expert systems to assist coral reef managers in decision-making.

8. *Remote sensing of coral reefs and other underwater ecosystems lags behind that of terrestrial areas, because of limitations of radiation penetration through seawater, and because of the low-priority historically given underwater ecosystem studies in the deployment of satellite sensors.*

Recommendations:

Design and deploy more high-resolution satellite sensors with finely divided bands in the visible (water-penetrating) light range. Find ways to lower the cost and improve the accessibility of airborne LIDAR and hyperspectral coverage in coral reef areas. Continue to improve the capacity of ship-borne acoustic mapping methods to determine ecosystem types and features. Improve the methods available for processing underwater images and for combining data from multiple sources into map products useful to scientists and managers.

9. *The potential for remote sensing to assist in coral reef and coastal management could be better realized by including watershed, oceanic and atmospheric remote sensing with reef-specific analyses.*

Recommendations:

Increase the availability of and develop better integration methods for the use of satellite and airborne sensor data to delineate characteristics of watersheds, classify human use patterns, determine average and extreme wave exposure, determine high-resolution sea surface temperature and water mass movements, quantify sunlight exposure and otherwise improve the basis for understanding changes on coral reefs. Improve coastal classifications using remotely sensed data to facilitate the conduct of analyses such as those of the Reefs at Risk Program, in which the real and potential exposure of reefs to degradation processes is inferred from a broad range of data (such as land use, water quality, geomorphology, etc.) and calibrated using reef-specific information. Higher resolution remotely sensed oceanographic data could greatly improve estimations of the impacts of coral bleaching events and assist greatly in studies of recruitment and connectivity among reefs. Educational materials should be produced to explain how a broad range of remotely sensed data could be used for management, employing case studies. The UNESCO Bilko for Windows Program and other analytical, educational and training systems could be utilized for this.

10. *There is yet unrealized potential for the use of remote sensing in support of the management of biodiversity and fisheries in coral reefs and associated environments.*

Recommendations:

Improve both our capacity to interpret remotely sensed data to identify and quantify ecological communities and our understanding of the species compositions of those communities under varying environmental conditions. Improve our capacity to identify these environmental conditions from sensor data. Use this knowledge to predict biodiversity patterns. Assess and improve the accuracy of these predictions via field studies. Explore and validate the use of remotely sensed data in identifying habitat attributes (such as fragility, vulnerability, etc.) for biodiversity planning and conservation prioritization. Conduct research into the use of remote sensing for producing ecological habitat maps in support of fisheries management, to assist in stock assessment, the delineation of critical habitats and the application of area-based management interventions such as marine protected areas.

11. *Remote sensing products of growing importance in studies of environmental changes over time are threatened with loss, damage or underutilization because of improper storage, inadequate record-keeping, costly or difficult accessibility, and by a lack of facilities and trained personnel across the region.*

Recommendations:

Develop an efficient, global system for finding and ordering or downloading all unclassified coastal and marine remote sensing products, including all extant aerial photography from government-sponsored surveys in the past. Link this to ReefBase, the Global Coral Reef Database. Support this dissemination with specific product development teams, such as an ocean color data dissemination team.

Translate relevant training materials, such as the UNESCO Handbook on Remote Sensing of Tropical Coastal Zones into all major Caribbean languages. Improve the availability of image analysis facilities, equipment and software among regional nations. Sponsor the development of remote sensing analysis facilities and computer-based training courses. Conduct training programs and sponsor advanced education in remote sensing applications to improve capacity throughout the region.

Connectivity Among Reefs

12. We do not fully understand the processes affecting the recruitment and retention of propagules, larvae and pelagic juveniles of coral reef organisms.

Recommendation:

Conduct studies of the life stages and population dynamics of coral reef species, and determine their relationship to physical oceanographic features and the geomorphology of coral reefs. Determine the processes affecting the survival of newly settled organisms. Investigate the population genetics of key species at multiple scales and estimate minimal viable populations sizes. Assess the biogeographic, within-habitat and depth distributions of coral reef species in support of understanding inter-reef dependencies.

13. Our knowledge of the nature of and relationships between local and large scale oceanographic processes is limited.

Recommendation:

Develop predictive models of regional oceanographic processes, along with estimated probabilities of certainty, at a variety of time and space scales, incorporating atmospheric processes. Validate and parameterize these models from greatly enhanced programs of data collection, including the use of ships of opportunity such as in the Sea Keepers Program, in which private and commercial vessels are outfitted with oceanographic instrumentation. A major emphasis should be placed on modeling the effects of climate change on these processes, on determining the implications for recruitment and retention of disease vectors, propagules and larvae, and the related impacts on the viabilities of fisheries and coral reef health in the future.

14. Many large-scale phenomena potentially play key roles in the ecology of regional coral reefs, but these roles are poorly known.

Recommendation:

Investigate large-scale phenomena including river plumes, upwellings and atmospheric dust inputs that affect the region to determine their influences on coral reef health.

15. Conservation of coral reef resources cannot be ensured without the coordination of efforts across the region based on knowledge of recruitment and connectivity processes, and of the interdependence among various types of ecosystems.

Recommendation:

Formulate a Caribbean-wide plan for ocean and coastal zone management, supported through international agreement, to guide and encourage the development of more effective management strategies and policies at national and local scales.

Reef Health and its Assessment

16. The relationships between biodiversity and ecosystem function in coral reefs, including the resistance to and resilience from disturbances, are unclear.

Recommendations:

Implement comparative investigations of coral reefs and their adjacent environments aimed at determining how calcification, nutrient cycling, resistance, resilience and other ecosystem functions vary under a range of environmental conditions, and how this variation relates to patterns of biodiversity. Long-term, large-scale studies should be a high priority, so as to account for variation in time and space. Research should include a focus on determining minimal sets of species and populations that must be maintained before substantial changes in ecosystem function occur. Studies should include further research on the means and cost-effectiveness of restoration techniques. Support research on factors important to ecological resistance and resilience, such as studies of key species' growth rates, timing of reproduction, fecundity, survival, settlement behavior interspecies interactions, and dependence on non-reef ecosystems. Use coral coring and paleoecological approaches to reinforce studies of ecological resistance and resilience over past decades, centuries and millennia.

17. Many patterns of migration, essential to the implementation of management interventions such as marine protected areas (MPAs), are poorly known.

Recommendations:

Conduct research into the migration patterns of fish and mobile invertebrates associated with coral reefs. Determine the relationships between migration patterns and ontogenic shifts, such as changes in feeding habits, fecundity and gender. Integrate this research into studies on the potential and empirically measured effectiveness of various MPA designs and geographic deployments.

18. There are a variety of "strong interactions" on coral reefs that require particular research focus in support of improved management. Some of these interactions, such as those between atmospheric CO2 and reef calcification, may change substantially over the next century, possibly resulting in wide-spread changes in reef viability.

Recommendation:

Conduct studies on calcification and coral colony growth vs. climate change, coral bleaching vs. seawater temperature, sedimentation vs. eutrophication, algal abundance vs. herbivory and nutrification, and storm frequency vs. extreme events such as El Niño. Strengthen research on atmospheric and seawater chemistry as it relates to coral reefs. Use coral coring and the fossil record in support of these studies. Focus research on determining the impacts on reef ecosystems of variations in bioerosion, diseases, fishing pressure and physical impacts by humans. Use this knowledge to develop more realistic ecological models to improve our knowledge of reef processes and to support better long-term reef management.

19. The assessment and monitoring of coral reefs and the evaluation of management interventions are often ineffective because of the variable levels of research capacity across the region, inadequate funding, and a paucity of meaningful, efficient and well-understood standard indicators and indices of coral reef health.

Recommendations:

Develop and standardize multiple independent indicators and indices for the assessment of reef health. Develop new stress indicators and validate these via long-term research. In cases for which point-in-time indicators are insufficient, protocols should be developed calling for robust time series of measurements to capture trends. Improve database development, implementation and communication in support of reef assessment and monitoring. Improve the capacity of countries throughout the region to assess and monitor reefs via improved infrastructure and training. Develop mechanisms for long-term, predictable funding of coral reef monitoring and of evaluations of management impacts.

20. Many of the species associated with coral reefs in the Caribbean are unknown in terms of taxonomy, systematics and phylogeny, and misidentifications are common due to the unfamiliarity by many field scientists with current knowledge in these areas.

Recommendations:

Strengthen research on the taxonomy, systematics and phylogeny of coastal and coral reef species throughout Caribbean nations. Sponsor the education of a new generation of scientists in these fields. Improve existing museum reference collections and develop new museums strategically across the region. Enhance education on these fields in universities and training courses, and develop tutorials for use on CD-ROM and via the Internet. Further develop computer-aided and molecular-based species identification procedures, and support research centers and museums to provide identifications as a basic service.

21. Many ecosystems involving reef-building corals are small or located in deep waters or the northern subtropics, and so have been little studied. Yet, they may be crucial to the maintenance of populations of reef species and of ecosystem function on a large scale, or have particular ecological or socioeconomic importance because of uniqueness and rarity in an area.

Recommendation:

Conduct biophysical-socioeconomic research on these "marginal" coralline ecosystems and determine their significance to population maintenance and ecosystem functioning across the region. Investigate how the sensitivities of these systems to local, regional and global disturbances and stresses differ from those of non-marginal reef systems. Identify any management needs that differ from those of better-known coral reef systems.

22. There is an increasing danger of species invading coral reefs from outside of their natural ranges, causing substantial changes in biodiversity and ecosystem health, and threatening resources vital to coastal populations.

Recommendation:

Initiate an organized research effort to determine the present and future levels of threats from invasive species, and potential impacts on reef-dependent people. Identify the means to limit the possibility of such invasions. Determine low-impact ways to remove invasive species as they appear.

23. It has long been recognized that many aspects of coral reef science cannot be properly investigated without highly interdisciplinary, large-scale and long-term research, and yet funding for this work is exceedingly difficult to find.

Recommendations:

Scientists and managers should form teams to develop well-engineered operational plans for integrated research efforts. These should include clear strategies for incorporating results into policy and management implementation, and estimations of the economic benefits that will likely result. Funding agencies and governments should increasingly set aside funds for organized long-term research as a means of improving overall cost-effectiveness. Groups of researchers should form agreements to use their usual sources to support collaborative research on specific reef systems.

Bleaching of Corals and Other Reef Species

24. The recent widespread bleaching of corals and other species has been clearly linked to sea water warming during El Niño related conditions, yet it is currently not possible to reliably predict the impacts, estimate the extent of damage or project the time to recovery after such events.

Recommendations:

Strengthen research efforts to use satellite maps of sea-surface temperature, stationary buoy systems and vessel-mounted oceanographic equipment, including the Sea Keepers' sensor deployment on vessels of opportunity, to provide early warning about bleaching events. Using a hierarchical research approach involving comparisons between broad area sea surface temperature estimates, fine scale remotely sensed temperatures, and field observations, determine the relationships between environmental characteristics, NOAA's "hot spots" and the incidence (per species) of bleaching. Use this as a basis for future estimations of the extent of bleaching based on the broad-scale NOAA satellite data. Improve these estimations through research on the physiological mechanisms involved in bleaching and potentially influencing factors such as the presence of disease, stress or recent perturbation. Improve channels to disseminate this information to managers, policy makers and the public.

25. Recent bleaching episodes indicate that corals can suffer mass mortalities as ambient seawater temperatures rise only one or two degrees above normal. Given that global climate change will result in such temperature increases being common, there is a potential threat to coral reef viability of substantial magnitude.

Recommendations:

Conduct research to model the future of the coral reefs under climate change, supplemented by enhanced research into bleaching, seawater chemistry, air-sea exchange and the natural mechanisms that might reduce coral reef damage, including adaptation of corals and/or their symbiotic "zooxanthellae" algae, and substitution by various species of corals and/or zooxanthellae. Improve the capacity to predict the long-term impacts of bleaching, in conjunction with various stresses and perturbations, and determine the conditions under which recovery is slowed or halted by shifts to macroalgal dominance. Use this knowledge to improve reef management so as to minimize the long-term effects of bleaching.

Diseases of Coral Reef Organisms

26. Although the coral reefs of the Caribbean are suffering from a recent, rapid proliferation of a variety of diseases affecting corals and associated species, we have little information on most of these diseases because of poor taxonomy of disease-causing microorganisms and the *organisms they infect, and the lack of research coordination, standards and reliable funding to analyze the diseases.*

Recommendations:

Enhance efforts on the systematics, taxonomy, characteristics and genetic composition of reef-related disease-causing microorganisms and the species they infect. Develop standards for analytical terminology and protocols. Use Koch's postulates, where appropriate, for determining causative agents and subject findings to peer review. Improve regional diagnostic capacity through improved facilities, training and higher-level education. Integrate recent advances in biotechnology into studies of reef-related diseases. Conduct research on patterns of susceptibility to disease and underlying physiological mechanisms. Identify disease vectors, natural reservoirs and extra-regional sources. Determine if diseases have been imported into the region through the introduction of exotic species, or transported by way of aquaculture, ballast water, the aquarium trade, dust storms from Africa or elsewhere, or other means. Identify the risks and potential means by which pathogens may be exported to coral reef areas outside of the Caribbean. Develop preventative measures for both import and export of these pathogens.

27. There is a paucity of information on the spatial distributions and time variability of reef-associated diseases, and their relationships to oceanographic dispersal processes.

Recommendations:

Implement studies of the biogeographic distribution and historical abundances of these diseases. Determine incidence, prevalence, host range, virulence and mortality rates by disease and host species. Integrate research on disease with that of reef connectivity, recruitment and physical oceanographic modeling.

28. The relationships between susceptibility to disease and environmental factors, stresses and disturbances are poorly known, and this hinders the efforts to minimize disease impacts through management intervention.

Recommendations:

Conduct research on the relationships between disease and environmental factors such as temperature, pH, water quality, UV light and irradiance. Determine the roles of pesticides, herbicides and combustion products that may contribute to disease through metabolic dysfunction. Identify critical thresholds for these factors and pollutants in their effects on disease susceptibility. Investigate the effects of stresses and disturbances acting in various combinations of type, frequency and intensity on susceptibility to pathogens. Determine if bleaching of corals or other zooxanthellate species increases this susceptibility. Investigate the possibility that diver activities, anchors and other mechanical disturbances enhance susceptibility of coral reef organisms to disease or spread infectious agents.

29. We need to know more about the relationships between pathogens and the infected organisms, their populations and the ecological communities of which they are a part.

Recommendations:

Expand studies of growth, reproduction and other organism-level processes with and without various types and levels of infection, and determine their relationship to disease susceptibility. Conduct immunology studies, including the responses of the genomes and proteins during infection (genomics and proteomics). Maintain supportive bioinformatics data analysis and storage systems, and associated networks. Determine the relationships of the diseases to reef microbiota. Determine the effects of the diseases on population dynamics (including fitness and changes in life stages), on community structure and on functional aspects of the ecosystems, such as resistance to and resilience from perturbation, given various types and levels of environmental stress. Explore the fossil record and coral cores to extend the basis for these studies into past decades and centuries.

Reefs at Risk in Caribbean

September 25, 2001

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Lauretta Burke

Background

In 1993, coral reef scientists estimated that 10% of the world's reefs were dead, and that 30% were likely to die within 10 to 20 years. This estimate was based upon the best available, but limited, survey data, and anecdotal evidence. In 1996, the World Resources Institute (WRI) launched a project to examine the state of the world's coral reef ecosystems and to assess the degree of threat to these systems. In June of 1998, WRI, in collaboration with the International Center for Living Aquatic Resources Management and the World Conservation Monitoring Centre released Reefs at Risk (R@R), a detailed, map-based analysis of threats to the world's coral reefs. The R@R analysis confirmed that coral reefs are seriously threatened in most parts of the world. The analysis estimated that 58% of the world's reefs are highly or moderately threatened by human activity—ranging from coastal development and destructive fishing practices, to overexploitation of resources, marine pollution, and runoff from inland deforestation and farming.

This initial analysis concluded that pressure on coral reefs within the Caribbean was slightly higher than the global average, with over 60% threatened. Thirty percent of the reefs are estimated to be at high risk, from sedimentation, inland activities, coastal development, pollution and overfishing.

We are in the midst of implementing a more-detailed regional-scale analysis of the reefs of Southeast Asia, where an estimated 80% of all reefs are threatened, and are planning a similar analysis for the reefs of the wider Caribbean. Working in collaboration with partner institutions throughout the region, this finer-scale analysis will yield more detailed and accurate results, which will be valuable for evaluation of alternative development plans, and for conservation priority-setting within the region.

Goals and Objectives

Effective management of Caribbean reefs is often hampered by a lack of information. The majority of the Caribbean's coral reefs have not been surveyed or consistently monitored over time. In addition, much of the data from monitoring has not been compiled or made publicly available. Although information from both scientific and volunteer surveys is increasing, this information is typically not well integrated with information on human activities that have the potential to contribute to the degradation of coral reefs. Development of an integrated base of information is the first step toward being able to better identify causes of reef degradation.

The Regional Reefs at Risk Project in the Caribbean has four primary goals:

1) Collect and integrate information to improve the base of information available for examining threats to, status of, and protection of coral reefs within the wider Caribbean.
2) Evaluate and model the relationships between human activities and reef condition, where available. Like the global R@R analysis, this will allow for extrapolation about threats to (and likely condition of) the many reefs for which survey information is not available.
3) Develop a geographic information system (GIS)-based tool for more local-level evaluation of development scenarios and related implications for coral reef health and economic value.
4) Raise awareness through wide dissemination of integrated data sets, model results, a published report, and the GIS-based planing tool.

Intended Audience

The outputs of the project are targeted for:

- Primary audience—national marine protection officials, policy-makers, and resource managers; trade and tourism ministers; international lending and development institutions;
- Secondary audience—NGOs and the general public; the scientific community

What is Proposed:

In collaboration with partner institutions in the region, we plan to implement a regional-scale analysis to link human activities with reef condition. The analysis will help to support conservation priority-setting through a systematic, data-rich analysis. This approach relies upon incorporating existing information on current threats to coral reefs, the condition and characteristics of surveyed coral reefs, and the level of protection afforded these reefs (through marine protected areas (MPAs) and other programs and incentives), coupled with estimates of economic and ecological value.

This analysis would be more detailed than the global Reefs at Risk analysis, both through implementation at a finer scale, and through broadening the analysis to include additional information where available on state of reefs, on biological diversity, socioeconomic factors affecting reefs, and economic value of reef resources.

The analysis of coral reefs would integrate a wide range of data:

A. *Threats to Coral Reefs* would be examined through a more detailed implementation of the Reefs at Risk methodology—development of refined decision rules, using more complete and higher resolution data sets to reflect threat, and more socioeconomic background information to provide context and to differentiate threats.

B. *State/Condition of Coral Reefs*—The global R@R analysis treated all reefs as a binary flag—presence/absence within a 4 km resolution grid cell. Within a regional analysis, we can incorporate the following additional information about specific reefs to differentiate reefs as to vulnerability and value:
   1. Information from existing monitoring programs about the condition of reefs
   2. Information on reef type and depth
   3. Information on biological diversity (species richness and endemism) would be incorporated at the highest resolution possible, along with estimation of the economic value of the biological resources and ecosystem services provided by the reef.

C. *Protection of Reef Resources*—Current global information on marine protected areas (MPAs) is poor. A richer and more detailed data set on MPA locations, extent and effectiveness could be developed in conjunction with local partners. This data "layer" is invaluable to the process of establishing conservation priorities. Additionally, information on coastal zone management and other policies relevant to pressures on reefs would be integrated.

All data integration and model results will be evaluated and revised based upon a workshop held in the region. Based upon the model implementation and results, we also plan to develop a GIS-based planning tool which allows examination of different coastal development and management scenarios and their implications for coral reef health, diversity and value. This tool would be developed and implemented with local partners.

Regional Extent of Analysis

The project will be implemented at two levels of detail:

1. Regional scale data integration and analysis—Initially, base data layers which are of consistent source and quality for the wider Caribbean will be collected and integrated, allowing for standardized comparison of threats to, condition of, and protection of coral reefs across the region.
2. More detailed analyses will be implemented with local partners. Countries and partners will be chosen opportunistically, based upon importance of the country in terms of coral reef holdings and diversity, and the contribution the partner can make in terms of data, expertise, and interest in the project. At a minimum, we intend to establish collaboration with partners in Cuba, Mexico, Belize, Honduras, Costa Rica, Jamaica, the Bahamas, and US Territories, but hope to establish similar relationships with partners in some of the smaller island states.

Analysis Components

We propose developing teams of partners to examine different threats to coral reefs. At present, we are proposing five analysis components to examine threats from:

1. Land-based sources of pollution and sedimentation;
2. Coastal development, including tourism development;
3. Marine-based sources of pollution;
4. Overexploitation, especially overfishing;
5. Coral bleaching

Collaboration

Collaboration will be critical to this project. We propose again collaborating with the International Center for

Living Aquatic Resources Management and the World Conservation Monitoring Centre, but wish to also work closely with more national and regional partners. These include UNEP's Regional SEAS program, the Island Resources Foundation, the Caribbean Conservation Association, the National Center for Caribbean Coral Reef Research (NCORE), the Atlantic and Gulf Reef Assessment (AGRA) and several national partners. Partners would be sources of data, expert advice on the methodology, and would serve as a site for implementation of the planning tool.

Expected Outputs:

1. Hardcopy maps reflecting best available mapping of coral reefs, and if possible, mangrove and sea grass habitats;
2. Hardcopy maps reflecting available information on coral reef condition, protection and threats to coral reefs;
3. Digital data sets reflecting best estimates of threats, value and protection status;
4. Full-color report summarizing findings, including maps of reef condition and threats to coral reefs;
5. Full-color poster of reef maps and summary of findings;
6. A webpage with information on the results of the project,—methodology, maps and policy recommendations;
7. A GIS-based planning tool for scenario evaluation, linking human activities with reef degradation.

Impact and Evaluation

Although the most important impacts of the Regional Reefs at Risk project will be long-term, there are some indicators that gauge project effectiveness in the near term. In looking back at the global Reefs at Risk analysis, we can look at the press coverage the report has received, the number of reports requested, the number of times the results are sited at professional meetings and in professional journals, the number of visits to the Reefs at Risk web site, and the number of users that have down-loaded the data from the web site. The global analysis was aimed at raising public awareness, and was very successful in this regard. The Regional project also has a goal of raising awareness, but the project also intends to improve the ability of policy makers in the region or working on the region to have good information and tools for decision-making. Here, we can assess project impact by the number of people in the region using the map and dataset outputs

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Remote Sensing and the Management of Caribbean Coral Reefs

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What can we map?

Satellite investigations of coral reef structure date back to 1975, shortly after the launch of Landsat MSS). Since then, the search for applications of satellite imagery to reef science and management has been almost exhaustive. Satellite imagery has been used for cartographic base mapping, detecting change in coastal areas, environmental sensitivity mapping, charting bathymetry, fisheries management and even stock assessment of commercial gastropods. The most widespread use of satellite imagery has been the mapping and inventory of coastal resources.

Remote sensing provides information on several parameters which are of importance to reef science and management (see Figure below). From a remote sensing point of view, the easiest of these to map are coral reef boundaries. The next level of sophistication is to distinguish principal geomorphological zones of the reef (e.g. reef flat, reef crest, spur and groove zone). For management purposes, such information may be used to provide a background for planning, but these maps may also have more sophisticated ecological uses which include the stratification of field sampling regimes. Mapping the ecological components of coral reefs (usually named "habitat mapping") appears to be considerably more difficult for remote sensing. Ecological components may be defined in various ways including assemblages of coral species, assemblages of coral and non-coral species, or assemblages of species and substrata. The choice depends on the ecological objective and physiognomy of the area. For example, coral species assemblages would be appropriate in places where coral cover was high, but perhaps less appropriate where coral cover rarely exceeded 20%. Maps of reef habitat are a useful planning tool which, among other uses, allow management boundaries to be located and the identification of representative reef habitats. Aerial photography and multispectral imagery have been used successfully to map tropical marine habitats whereas satellite-borne sensors seem to be unable to map habitats in detail.

Moving beyond mapping reef habitats to the status of individual coral colonies, it seems likely that only high resolution (low altitude) airborne methods will be successful. To date, there is limited evidence that coral cover and algal cover can be mapped routinely using remote sensing. Infrared aerial photographs have been used to detect living coral colonies in very shallow water (<< 1m) in Thailand but the dependence on shallow water deems the method unsuitable for the majority of Caribbean reefs. Recent work in French Polynesia set a precedent for distinguishing living and recently-dead coral to a depth of 7m using airborne imagery but the representativeness of these results are still being evaluated. Coral or algal species discrimination does not appear to be possible.

Future challenges in coral reef remote sensing

1) *Progress in mapping:*
   Most deleterious processes on coral reefs such as nutrification and overfishing result in reduced coral cover and increased algal cover. Detecting changes in coral and algal cover is therefore a key goal of remote sensing. Although coral and algal cover can be mapped using remote sensing where conditions are optimal (i.e. clear, shallow water), the limitations of the methods have yet to be evaluated. Radiative transfer models are required to test the overall limitations of remote sensing for measuring the health of coral reefs. This is particularly pertinent for the generation of new high-resolution satellite sensors such as IKONOS with 4 m pixels. New methods are also required to mitigate the continuing problems of variable water depth and pixels containing mixtures of substrata.

2) *Mapping the locations of reefs:*
   A surprising additional challenge for the remote sensing community is the basic mapping of the World's coral reefs. Despite 30 years of reef remote sensing, many reefs have never been mapped although such maps are needed to understand the connectivity between reef systems and develop transboundary coastal management initiatives.
3) *Applications of remote sensing for biodiversity assessment:*
   Remote sensing can provide an overview of the distribution and abundance of marine habitats. The use of such information for managing benthic diversity and reef fisheries has barely been explored. For example, can habitat maps be used as a surrogate for other levels of diversity? In a related vein, recent studies have used the long time series of Landsat imagery to detect general increases in macroalgal abundance resulting from the loss of *Diadema antillarum*.

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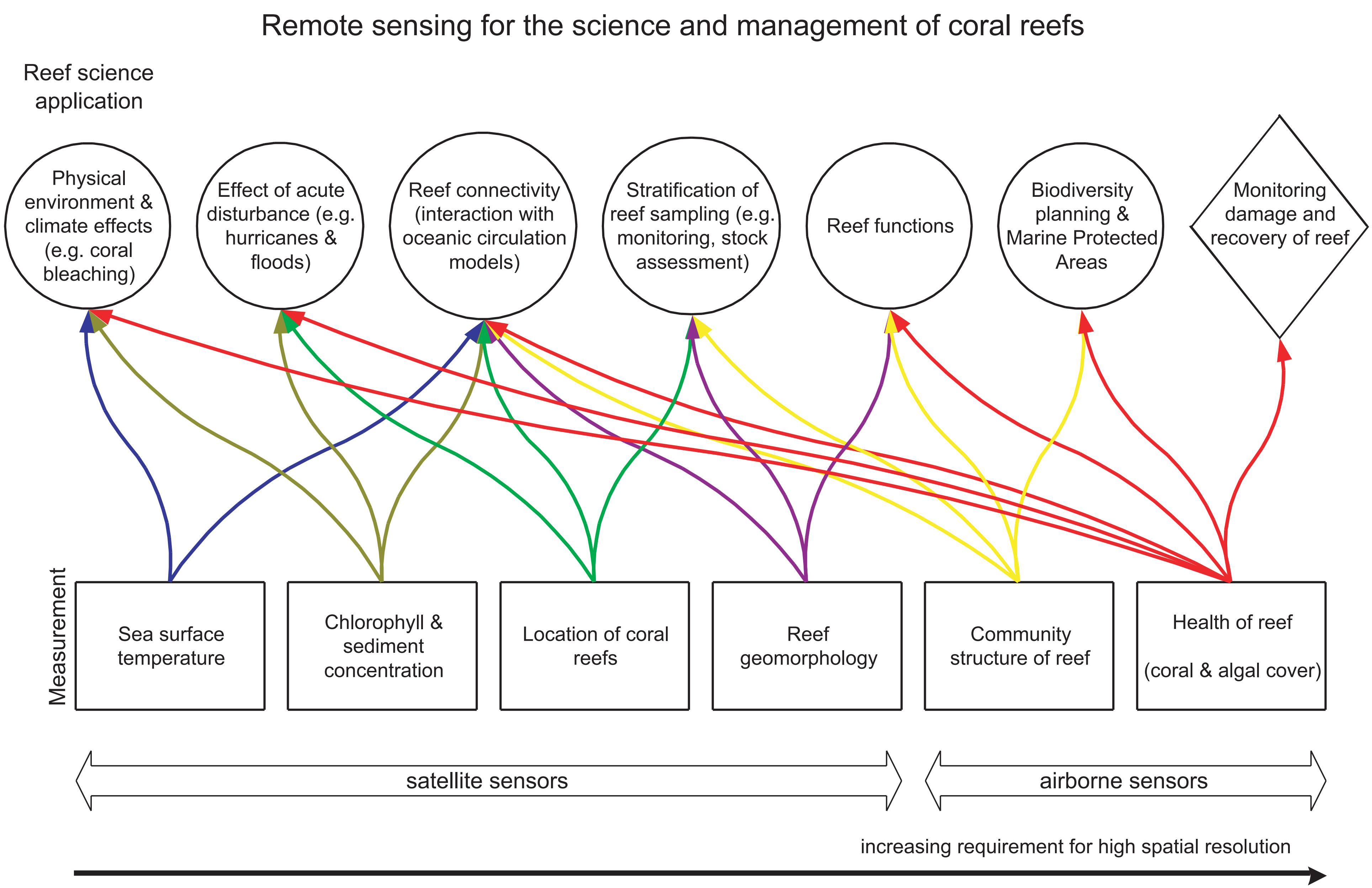
Remote sensing for the science and management of coral reefs
Reef science application
Physical environment & climate effects (e.g. coral bleaching)
Effect of acute disturbance (e.g. hurricanes & floods)
Reef connectivity (interaction with oceanic circulation models)
Stratification of reef sampling (e.g. monitoring, stock assessment)
Reef functions
Biodiversity planning & Marine Protected Areas
Monitoring damage and recovery of reef
Measurement
Sea surface temperature
Chlorophyll & sediment concentration
Location of coral reefs
Reef geomorphology
Community structure of reef
Health of reef (coral & algal cover)
satellite sensors
airborne sensors
increasing requirement for high spatial resolution

Mumby–3

Priorities for Caribbean Coral Reef Research

Scientific Needs for Integrated Coastal Management and Fisheries

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Janet Gibson[1] and Melanie McField[2]

In the early nineties scientists and managers came to a general consensus that the three major stressors on Caribbean reefs were siltation, overfishing and nutrient enrichment (Ginsburg 1994). As the sources of these stresses often originate from land-based activities, reef protection requires a fully integrated coastal management approach (Gibson *et al.* 1998; Salm *et al.* 2001), often requiring international co-operation. In recent years threats associated with global climate change, such as coral bleaching, have greatly impacted many reefs and added to the complexity of management

Although the management approaches required to protect coral reefs mainly pertain to the management of people (Olsen 1997; Hatcher 1999), the decisions made must be based on good science. The interconnectedness of the components of the system is paramount, as was clearly demonstrated in the work carried out on the north coast of Jamaica in which overfishing indirectly resulted in the inability of corals to recover after a natural disturbance (Hughes, T.P. 1994; Knowlton 1998). In view of this ecological complexity, it is even more imperative that science is applied to management, and where knowledge is lacking that the precautionary principle be applied (Knowlton 1998). However, in developing countries where the pressure for economic growth and development is high, there is an urgent need for assistance in making the 'best' decisions in absence of full quantitative data, and in an effort to best fulfill multiple objectives (Fernandes *et al.* 1999).

Scientific needs to inform integrated management of coral reefs include improved understanding of how the ecosystem functions, how it responds to natural and anthropogenic changes, and also the effects of management strategies implemented (McField 2001). Evaluating effectiveness of management requires the selection of indicators that relate to specific management objectives (Olsen 1997). The identification and formalizing of such an evaluation process would be helpful to managers. As Hatcher (1999) noted, monitoring, multiple use zoning as used in many marine protected areas, and decision support systems should underpin most reef management programmes. These require analysis of the social, economic and institutional issues in relation to a reef (Olsen 1997), and thus need to be site specific. Thus, broad concepts developed from studies at specific sites cannot always be successfully applied to reefs having very different environmental settings and histories (McField 2001), or to areas with different cultural and socio-economic backgrounds (Olsen 1997; Hatcher 1999). Some priority needs that would be useful to coastal managers are hereby suggested.

Marine protected areas (MPAs) are generally recognized as being at the centre of integrated coastal management (ICM) efforts, but there are many unanswered questions about their optimum size, location and general effectiveness. In terms of size, although some recommendations have been made (e.g. Bohnsack 1990), the accurate percentage cover of 'no take' area required for a particular reef is still largely unknown. The factors involved depend to some extent on the organisms being targeted for protection. For example, Acosta and Robertson (2000) have recommended changes to the boundaries of a MPA in Belize based on the movement of spiny lobster. In addition, more research is needed to demonstrate clearly the role of MPAs in fisheries management, for example their potential to export fish, maintain levels of spawning biomass, and their ability to protect spawning aggregations included within their boundaries. The theoretical benefits of increased herbivory in MPAs contributing to reduced macroalgal cover have recently been tested in Belize through several different experimental or analytical approaches (McClanahan *et al.* 2001; McField 2001; Williams & Polunin 2001) although the combined results have not been conclusive. MPA networks should include areas of 'downstream reefs,' but to ensure this connectivity between MPAs many more studies are required on current patterns, dispersal paths, larval durations and

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settlement requirements, and also on initiating MPAs across borders (Russ 1996; Roberts 1997). Research has been proposed to identify coral reef areas that show resilience to bleaching events, and these critical areas can then be included within MPAs. In general, a great deal more work is required to determine with confidence, the most effective MPA network for a particular reef system, bearing in mind that MPAs are often costly to run successfully. The interactions between nutrients, algal dominance on reefs, herbivory, and coral cover are very complex (McCook 1999; Aronson & Precht 2000; Williams & Polunin 2001). Many Caribbean reefs are experiencing a phase shift from coral cover to algal cover (Hughes 1994; McClanahan & Muthiga 1998; McClanahan *et al* 1999). Although studies have shown that overfishing of herbivorous fishes is not the only factor causing an abundance of macroalgae (Williams & Polunin 2001), it would be useful to investigate whether re-introducing and protecting herbivores (e.g. parrot fish, *Diadema*) on such reefs would be successful.

The effect of fishing on reefs is very complex and more studies are required, for example, to develop the ability to predict its role in causing shifts in the ecosystem (Jennings and Polunin 1996). Different fisheries management strategies could be tested, such as the harvesting of mainly pelagic species which rely on external sources of food, or fishing at all trophic levels thus using a broader resource base. MPAs could provide the sites for such studies to be carried out. Refined modeling techniques could assist in determining fish yields under different strategies, using more appropriate catch and effort data that also includes information on invertebrates and plants (Jennings & Polunin 1996). More needs to be known about reef algae (reproduction, dispersal and recruitment), coral–algal interactions, bioindicators of reef nutrient status and the advantages of using stable isotope analysis of coral tissue (Risk & Risk 1997; McCook 1999).

A better understanding is required of the impacts of chronic stresses, such as sedimentation and nutrification, which may be low under stable conditions, but which may adversely affect coral recovery in times of major disturbances such as bleaching and hurricanes. This type of evidence would be useful to managers in gaining the necessary support for the need to reduce human impacts. The results of monitoring can be used in public awareness and education programs to generate the necessary community support (Hatcher 1999).

Nevertheless, these impacts are the chronic, gradual ones which are often difficult to demonstrate cause-and-effect to decision makers. Recent work, however, is attempting to develop a multivariate approach to address this need (McField 2001). In contrast, the more dramatic impacts of storms and bleaching, such as the 48% decline in coral cover experienced in Belize (McField in press) are clearly noticeable in the short term, and can frustrate local efforts because they occur outside the control and limit of national management responsibility.

Many of the human impacts result from land-based activities, and much more research still needs to carried out in basic areas, such as determining the potential of mangroves to absorb nutrients from effluent discharge from sewage ponds and aquaculture farms, developing low-tech water reuse systems for shrimp farms, identifying the main causes of increased sediment yield at the scale of individual farms, assessing the effect of farming practices on nutrient loading in the coastal zone, and determining the influence of river run-off on reefs (Done 1995; Nunny *et al.* 2001). From these studies, improved land management practices can be recommended.

Determining the most relevant scale of potential impacts on reefs is a particularly complicated task for scientists, but critical for managers needing to know whether concern over nutrient enrichment should be focused on localized septic runoff, regional fluvial/agricultural discharges, or global dust storms.

Dive tourism is a major activity on many reefs in the Caribbean. However, determining carrying capacity is a prerequisite for limiting dives per site, and this is often difficult to assess. Although some work has been carried out (Hawkins & Roberts 1997; Jameson *et al.* 1999, Hawkins *et al.* 1999) more assistance from scientists is required in determining optimum sites for installing mooring buoys, the size of groups of divers per site, the effectiveness of rotating sites as a management measure, and the type of monitoring required. In Belize a mooring buoy impact project is currently underway at Lighthouse Reef and another study is planned for Hol Chan marine reserve, our most heavily visited site.

Simple methods for valuing reefs are required and may depend on use of a reef for tourism, fisheries productivity, and biodiversity. The criteria for determining the value need to be worked out so that managers can assess the consequences of loss of a reef put at risk by a development, or damaged as a result of ship groundings, etc. Such a 'value' can be used as a basis for the design of environmentally friendly development and land use practices (Done 1995). Fernandes *et al.* (1999) have used a multiple criteria analysis framework that assesses the multiple objectives of management—economic, social, and ecological—many of which may be conflicting. This integrated systematic assessment seems to be worthy of more research as it incorporates both quantitative and qualitative data and includes provision for community participation. The technique has some flaws, but further work could possibly make it more robust and usable by managers. One such evaluation was recently initiated at Lighthouse Reef in Belize with researchers from the University of Stockholm. Socio-economic analyses are critical to placing conservation measures into an economic context, understandable to developers and the general public.

Assessment and monitoring are basic elements of ICM, laying the scientific foundation for sustainable reef management (Wells *et al.* 1996). Surveys and assessment provide information on the extent and status of the system to be managed, identifying areas of high biodiversity. It is essential to have baseline data on the status of the system to be managed, and to measure or monitor changes over time in response to various impacts and management interventions. Monitoring should focus on the most likely sources of stress and thus lead to the most appropriate mitigation programmes (Risk 1999). More research is required to determine simple, cost-effective, and community-based methods, preferably developed for monitoring special indicator species (Risk & Risk 1997). Several potential indicator species (e.g. sponges, stomatopods) have been identified, but few have been rigorously tested (Turner 1995). More focus should be placed on monitoring techniques for determining recruitment rates and factors affecting recruitment, thus helping to accurately predict the recovery time of degraded reefs. However, much time and energy can be wasted on lengthy discussions/disagreements over monitoring methods, which could be better spent in collecting the information. More work is also needed on determining factors affecting spawning of corals and dispersal of larvae. Once again, this will require more research on currents of the region, particularly on local near-shore currents (Roberts 1997). Such studies could help identify those reef areas that are dependent on local management measures to maintain fisheries and biodiversity, in contrast to those that have an 'upstream' or external larval supply (Roberts 1997). A wide range of research needs could be pursued that are interdisciplinary, integrating the efforts of natural and social scientists, and which could result in support from decision makers for adaptive management for the protection of the region's coral reefs. Managers must also work within the local cultural and political climate to implement their management decisions, which may prove difficult for reasons beyond the realm of science.

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Coral Reef Health, Connectivity, Assessment and Monitoring

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Eric Jordán-Dahlgren

According to many sources, coral reefs as we know them, are declining to a variable extent. Multiple stressors, both human induced and natural, seem to be responsible for mortality events among different elements of the coral community. Although it is now possible to identify or infer causes of mortality or degradation in many instances (bleaching, diseases, over-fishing; habitat destruction, etc.), we also have become aware that reefs are highly variable and may react differently to apparently similar stressors. As a consequence reef robustness, resilience and fragility are relative terms that vary along a wide time-space scale, and therefore difficult to use for predictive purposes. Our limited understanding of the ecological processes and interactions at the populational and community level, and of the oceanographic dynamics that modulate ecological connectivity, hampers our ability to interpret the long term effect of changes of state in the coral community, whether it be degradation or recovery. On a global scale we still are trying to assess the condition of reefs, and although we have achieved good results, so far our limited knowledge on the complex dynamics of the reef ecosystem makes it difficult to identify unique indicators of reef health. Monitoring change in coral community structure or key coral populations is necessary to increase our understanding of coral community responses. But unless the monitoring is designed to evaluate—at adequate temporal and spatial scales—the effect of suspected stressors, its utility will be reduced merely to documenting change and not helping to explain why the change occurred. Given that there is now compelling evidence of degradation in coral reef systems, and that our need to better understand the context under which degradation and recovery occur is becoming more urgent by the day, this understanding may have far reaching implications for proper conservation and management strategies.

Caribbean Coral Reef Diseases, Status and Research Needs

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Over the past decades coral reef communities around the world have been experiencing increasingly stressful conditions due to the combination of natural and anthropogenic detrimental factors. Coral reefs around the Caribbean have experienced significant loses in hard coral cover due in part to local habitat (coastal and/or inshore) degradation, over-fishing and pollutant input. However, in the last two decades, disease outbreaks have played an important role in the loss of coral cover and the deterioration of Caribbean reefs. The combination of these factors with mortalities produced by more frequent and intense bleaching events and storms without intermittent periods of good conditions for recovery, might prove lethal for these communities.

Current status

The Caribbean is viewed as a "Hot Spot" due to the increase in frequency of epizootic events and fast emergence of "new" diseases associated with corals, octocorals and other reef organisms (Table 1). Like other emerging diseases, many coral syndromes represent new types of pathologies, or recurrent, more virulent old forms. Even though reef-related diseases have been studied and described since the late 1970's, only recently, research to characterize coral/octocoral diseases have been undertaken. This research has revealed an impressive diversity of microbial pathogens, ranging from single fungal or bacterial species to loose- or tightly structured bacterial consortia. This pathogenic microbiota includes phototrophic and heterotrophic species that show a wide range of metabolic modes. Nevertheless, despite the increased effort to identify and characterize pathogens affecting corals, only five of the seventeen-plus different coral/octocoral diseases and syndromes put forward by researchers in the Caribbean (Table 1), have their causative agent identified: black band disease (BBD), white plague type II (WP-II), aspergillosis (ASP), white band disease type II (WBD-II), and more recently, white pox disease (WPX). However, Koch's postulates have been fulfilled for only three of these (WP-II, ASP and WPX). Bacterial bleaching is another syndrome with a well-characterized pathogenesis but which is poorly understood in the Caribbean. According to the Global Coral Disease Database, which compiles information on the range of species affected and the geographic distribution, incidence and mortality for each disease, 29 differently named diseases have been reported with BBD, WBD, WP and ASP accounting for 80% of the 2076 worldwide records in the database.

Some minor advances have been made in the characterization of other common syndromes such as dark spots disease (DSD) and red band disease (RBD). On the other hand, the mechanism causing host's tissue mortality is only known for BBD. Despite efforts by different research groups, some pathogens of common and widespread afflictions such as yellow blotch disease (YBD) and white band disease type I (WBD-I) remain elusive. Disease reservoirs have only been identified for BBD (biofilms of non-pathogenic BBD consortium in reef sediments) and ASP (atmospheric African dust). Many other syndromes remain to be characterized. The different types of the "same" syndrome (i.e. WBD-I and WBD-II) refer to different etiologies of the same disease. White plague-I described for the Florida Keys, did not affect many species and had a slower rate of advance compared with WP-II (more virulent and affected more species), or the more recent WP-III observed in Florida and other areas of the Caribbean, which seems to be even more virulent and shows a different pattern of spread over the colonies. Preliminary results indicate, however, that a common pathogen may be associated with all forms of WP. If so, changes in host susceptibility, perhaps induced by environmental change, may account for epizootic variability.

For most diseases, there is limited information on aspects of the etiology, ecology and epizootiology (such as rates of incidence and variability at local, geographic and temporal scales, disease local and geographic distribution, and host ranges and variability across the region). Most reports are from local, short term epizootic events. Nevertheless, a recent survey of 19 reefs sites from 6 widespread geographic localities (Bermuda to Colombia) has provided important information on these aspects. Results indicate that WP-II, YBD, BBD, and ASP are distributed throughout the wider Caribbean, and that the average incidence of diseases, in general, seems to be low at the coral community level (3.02%), but it varies significantly at local and geographic scales. Disease incidences at the population-species level were higher (Table 3) but, highly variable locally and geographically. Aspergillosis is affecting the higher proportion of colonies (5.56–30.56%) of an individual species (*Gorgonia ventalina*) followed by DSD (0.16–7.61%), WP-II (0.11–3.20%), and WBD (0.07–0.41%). Results also indicate the number of coral (most of them, important reef-building species) and octocoral species susceptible to at least one disease/syndrome in the Caribbean has increased to 38 and 10, respectively, in recent years (Fig. 1). The GCDD reports 102 coral species from 54 nations across the world as being susceptible to at least one disease. The host range of most of the known diseases has also increased in recent years, WP-II has the widest host range infecting at least 32 coral spp., followed by BBD (16), DSD (DSD) (12), YBD (7) and WBD (3). ASP increased its host range from two species in a single genus of sea fans to 10 spp. in at least four of the most common and widespread genera of octocorals in the Caribbean (*Plexaura*, *Plexaurella Pseudoterogorgia*, and *Pseudoplexaura*). Five important reef-building corals in the region (all four species of *Montastraea* and *Colpophyllia natans*) are each being affected by five different disease/syndromes.

Not all disease colonies face total mortality (as opposed to partial mortality) however. *G. ventalina* colonies react to the fungal disease and are capable of restrain its advance by sequestering the hyphae in hard structures called galls. BBD seems to be sensible to changes in the light and temperature regimes, usually halting its advance when water temperatures drop. In Bermuda for example, thirty-five tagged coral colonies affected by BBD in the summer of 2000 were all alive, without traces of the disease, and re-growing lost tissue in the summer of 2001. Similar recoveries have been reported for Florida. This however, may vary at lower latitudes where water temperatures and light regimes are less variable. These results suggest that even though there are no chronic epidemics in the region, the combination of diseases (widespread distribution of most disease/syndromes, high incidence of some diseases in many of the important reef-building species and recurrent epizootics, wide host breath) with the other detrimental environmental pressures, might prove lethal to reef communities throughout the Caribbean. However, before we speculate what the outcome of the current events might be, we need more information and epidemiological models developed with sound quantitative data.

Possible Causes

Even though it has been difficult to explain the source(s) and sudden emergence of the majority of the diseases/syndromes, recent reports suggest that this phenomenon might be related to the deteriorating and changing environmental conditions in the region, which can increase the prevalence and virulence of existing disease, or facilitate new diseases. Climate changes such as the current warming trend and its consequences (i.e. increase water temperatures, more frequent and intense ENSO events, bleaching events and storms, etc.) could affect basic biological (physiological) properties (and/or balances) in parasite and/or host populations, making them more virulent and/or more susceptible to disease. The emergence and widespread distribution of some diseases in the Caribbean might also be associated with increased amounts of African dust moving into the region, increased sediment runoff from deforested tropical areas, etc. Spores of the fungus *Aspergillus sydowii,* the species responsible for the sea fan disease ASP, have been found in the African dust.

Today, marine pathogens can be moved faster and for longer distances by human activities such as commercial shipping, movement of war ships, and the transport of marine species (aquaculture, aquarium trade, etc). Widespread epizootic events can then result when new or more virulent pathogens emerge, when pathogens move in from another region, or when physiological balances between host and parasites are disrupted (stressful conditions). Many recent mortality events seem related to the emergence of new pathogens, or more virulent strains of common ones (Table 1).

Problems

Even though the general aspects of coral diseases and their etiology and epizootiology have been recently reviewed by various authors (i.e. Santavy and Peters, 1997; Richardson, 1998), there is still limited (or lack of) quantitative data and information on the pathology and etiology of most diseases/syndromes affecting reef organisms. The inability to explain the source and sudden emergence of the majority of coral reef's diseases/syndromes is just one of the problems in this field. We do not know the pathogenesis for the majority of the syndromes observed and therefore, most diseases have been named according to their ecological characteristics (not pathology) creating confusion in the number of diseases/syndromes present. We do not know the mechanisms by which most diseases kill their hosts, what their rates of spread and host mortality are, and how these parameters vary within and across host species, and how they vary on spatial and temporal scales. Consequently, there is lack of information on the different disease's spatial and temporal variability in incidence, pathogenesis, and their local and geographic distribution. Without this information, it is difficult to assess significant changes in their temporal and spatial distribution, their epidemiology, and most importantly, their potential detrimental effects at the population and community levels at local and geographic scales. We need more information on all these aspects, and to start thinking about potential and practical remedies for some of the most destructive diseases (i.e shading corals with BBD usually will get rid of the disease).

Ecological consequences

Widespread, intensive epizootic events may play important roles in the deterioration and/or changes in community composition, structure, and dynamics at local and geographic scales. Two such events affecting "key" species in the Caribbean are mostly responsible for shifts in the structure of coral reef communities from coral-dominated to macroalgal-dominated in many reef localities of the Caribbean: (a) the disease-induced mass mortality of acroporid corals and (b) the mass mortality of the black sea urchin *Diadema antillarum*, a major herbivorous and bioeroder species on Caribbean reefs. Populations of these species were reduced to unprecedented low levels, changing the community structure of shallow coral reef habitats and the algae communities within coral reefs and sea grass communities. To this day, no one knows what killed the black urchins due to very limited pathological studies at the time and the absence of frozen or preserved samples which could be studied using modern techniques. Other minor local mortalities with no apparent detrimental ecological impacts in marine communities have also occurred in many localities across the region (octocorals in Central America and Trinidad, urchins and sea grasses in the northern Caribbean and Florida, Belize, Venezuela, and Puerto Rico, etc.) (Table 1).

Increasing evidence seems to point to the fact that diseases stand out as an important, if not the most, forcing factor affecting major groups of reef-forming organisms and therefore, significantly contributing to the deterioration of coral reef communities around the Caribbean. Disease has become a crucial factor in the recent dynamics of Caribbean reefs, and limited paleontological evidence suggests at least that the WBD outbreak that killed the acroporids in the Belizean lagoon, was unprecedented on a time-scale of the last three millennia at least. Management programs need to take into account the fact that marine reserves most likely will not protect coral populations from regional-scale, water-borne pathogens, such as the ones that probably caused the *Diadema* mass mortality, and other epizootic events such as WBD-I, WP-II and ASP.

Research priorities

1) Identify and characterize the pathogens (fulfilling Koch's postulates) for at least the most virulent diseases/syndromes reported. This will probably have to be done for all species affected to verify the identity of what is now supposed to be the same agent. Develop a quick probe (test) that will simplify process.
2) Characterize each disease's etiology and epizootiology on temporal and spatial scales, with clear descriptions of the signs and variations within and across species and across geographic regions.
3) Determine the local and geographic distribution of each important disease / syndrome
4) Increase the collection of quantitative data to determine the rates of incidence of each of the major coral/octocoral species affected and what the incidence variability is between populations within the same geographic locality and across geographic localities.
5) Complete information on the host ranges of each important disease
6) Develop monitoring programs to gather information on partial mortality rates (tissue loss), colony mortality rates, recovery rates, and changes in the host ranges of each disease.

Table 1. Reported mass mortalities (> 10% within population) by pathogens of different marine organisms in the wider Caribbean since 1938, their associated pathogen, estimated mortality and environmental correlate (T = temperature, Sal = salinity). CA= Caribbean, ATL= Atlantic.

Date	Host spp.	Location	Pathogen	Mortality (%)	Env. Correlates	Source
1938	SPONGES	North-CA	Fungus ?	70-95	ND	Gatsof et.al. (1939)
1946	OYSTER (*Crassostrea*)	Gulf coast	*P. marinus*	High	High T, Sal.	T.J. Soniat (1996)
1980	URCHIN (*Strongilocentrotus*)	NW- ATL	*Amoeba??*	> 50	ND	Miller & Coloday (1983)
1981	CORAL (Acropora)	CA - wide	Bacteria ?	70-95	ND	Gladfelter (1982)
1982	OCTOCORAL	Central Am	??	High	High T	Guzmán & Cortés (1984)
1983	CORAL - several species	CA - wide	Bacterial cons.	Variable	Seasonal	Ruetzler et.al. (1983)
1983	URCHIN (*D. antillarum*)	CA - wide	??	> 95	High T	Lessios et.al. (1984)
1987	SEA GRASS (*Thalassia*)	FLORIDA	Slime Mold/fungus	<95	High T, Sal.	Roblee et.al.(1991)
1988	MOLUSC (Argopecten)	North-CA	Protozoan	High	ND	Moyer et.al. (1993)
1995	OCTOCORAL (*G. ventalina*)	CA - wide	Fungus	High	ND	Nagelkerken et.al.(1996-97)
1995	CORALS (*Dichocoenia* & others)	FLORIDA	Bacteria	<38	Seasonal	Richardson et.al. (1998)
1996	CORALS (*Diploria* & other spp.)	P.RICO	Bacteria	High	Seasonal	Bruckner & Bruckner (1997)
1997	URCHIN (*M. ventricosa*)	CURACAO	Bacteria	High	Pollution?	Ritchie et al. (2000)

* Modified from Harvell et. All (1999)

Figure 1 . Number of coral/octocoral species affected by each disease/syndrome. HYP= hyperplasias; OTH = other syndromes.

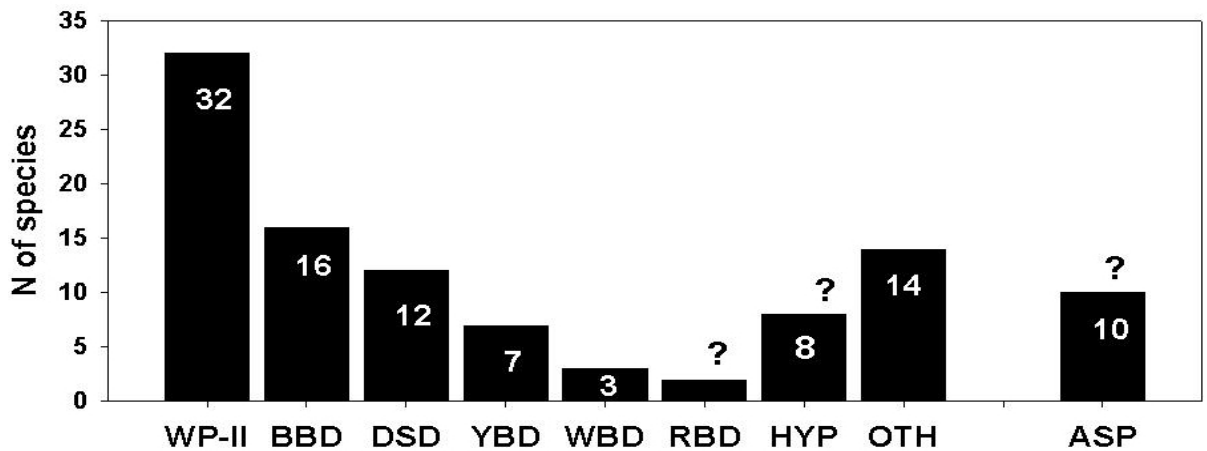

Table 2. List of Caribbean ©, Atlantic (A), Indo-Pacific (IP, and Red Sea (RS) reported coral/octocoral diseases, their acronym, Identified pathogens, groups and/or species affected. Numbers in parenthesis are the number of species affected in each group.

Syndrome/Disease	*Acronym*	Pathogens	Species	Distrib.	Source
Black Band Disease	**BBD**	***P.corallitycum, D. vibrio, Beggiatoa spp..***	**Corals (16)- octocorals**	**C,A,IP**	**Antonious, 1970-1973.**
					Ruetzler & Santavi, 1983.
White Band—I	**WBD- I**	**Gram (-) bacteria**	**Corals (Acroporids) (2)**	**C**	**Gladfelter et al., 1977.**
White Plague—I	**WP- I**	**Gram (-) bacteria**	**Corals (17)**	**C**	**Dustan, 1977.**
Shut Down Reaction	**SDR**	**????**	**Corals**	**C**	**Antonious, 1983.**
Tissue Hyperplasia	**TH**	***E. endozoica (algae)***	**Octocorals**	**C**	**Goldberg et al., 1983.**
Hyperplasia	**HYP**	**????**	**Corals (4)**	**C**	**Weil, unpublihsed data**
White Band—II	**WBD- II**	***Vibrio charcharii***	**Corals (Acroporids)**	**C**	**Ritchie & Smith, 1998.**
White Plague—II	**WP- II**	***Sphignomonas sp.***	***D.stockesii and others* (17)**	**C-A**	**Richardson et.al., 1995.**
Aspergillosis	**ASP**	***Aspergillus sydowii***	**Octocoral spp (10)**	**C**	**Smith et.al., 1996.**
Yellow Blotch	**YBD**	**????**	**Favid corals (7)**	**C-A**	**Santavi et.al., 1999.**
Red Band	**RBD**	**????**	**Octocorals—Agaricids?**	**C-A**	**Richardson, 1998.**
White Pox I	**WPX- I**	**????**	**Acroporids (2)**	**Florida**	**Porter, 1998/Weil P.obse.**
Rapid Wasting	**RWS**	**????**	**Favid corals (3)**	**C**	**Goreau et.al., 1997.**
Dark Spot—I	**DSS - I**	**????**	***Siderastrea spp. (2)***	**C**	**Garzon, 1998,**
Dark Spot—II	**DSS - II**	**????**	**Corals (12 spp)**	**C**	**Goreau et.al., 1997.**
Yellow Blotch	**YBD**	**????**	**Corals**	**RS**	**Korrubel & Riegel, 1998.**
Poritid Disease	PX- II	bacteria	Poritid corals (1)	IP	Reynolds et al. (2000)
Ring Disease	**RD**	**????**	***D. labyrinthiformis***	**Bermuda**	**Weil, unpublihsed data**

Table 3. Average disease incidence (%) in major reef-building coral species across five geographic localities in the wider Caribbean. ND = no data, ----- = not present or uncommon

Species	Bermuda	PRico	Bonaire	Colombia	Venezuela
A. palmata	-----	1.31	2.5	14.97 #	28.13
A.cervicornis	-----	1.15	3.39	39.58	0.37
M.faveolata	-----	4.65	9.05	10.37	8.38
M.annularis	-----	5.45	12.55	12.58 #	5.84
M.franksi	1.1	2.29	3.32	5.6	2.02
M.cavernosa	0.15	0.53	0.43	5.99	0.83
D.strigosa	1.3	2.13	0	7.15	1.11
D.labyrinthiformis	0.08	0.99	0	7.23	0
S.intersepta	0	0.22	5.61	12.19	6.76
S.siderea	0	5.32	16.5	12.3	11.05
P.astreoides	0.15	0.79	0	1.54	1.3
P.porites	0	0.53	0	0.45	0
D.cylindrus	-----	6.67	0	-----	2.1
D.stokesii	0	4.63	0	16.2	0
D.stellaris	-----	4.12	0	-----	0
C.natans	0	0.54	0	6.68	0
A.lamarcki	-----	4.13	0	0	0
G.ventalina	12.55	8.08	18.67	ND	10

(Weil, unpublished data)

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Coral Reefing: Caribbean Events and Some Problem Areas for Future Research

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Many workers now link coral reef bleaching and mortality with stressful elevated sea temperatures resulting from greenhouse warming conditions, particularly evident during the past two decades. Since the early 1980s this type of disturbance has been observed in all of the world's major Indo-Pacific and western Atlantic coral reef regions. Coral reef bleaching has occurred over the entire western tropical Atlantic region, from Bermuda and the Bahamas to the Florida Keys, the Gulf of Mexico, the greater Caribbean region and Brazil. Within this region, the severity of bleaching events have varied widely, e.g. in 1998 from minor bleaching (< 5%) and mortality (< 1%) at the Flower Garden reefs in the Gulf of Mexico (Wilkinson, 2000) to nearly universal bleaching (~ 100%) of all zooxanthellate species and ~ 100% mortality on central shelf lagoonal coral reefs in Belize (Aronson et al., in prep.). By some global climate models, if the seas' temperatures continue to increase at a projected rate of approximately 1 to 2°C per century, the upper thermal tolerances of reef corals would be exceeded, leading to mass coral mortalities in the next 30 to 50 years (Hoegh-Guldberg, 1999). Because of the severe negative responses thus far observed, it is urgent to assess the causes and effects of thermal stress on coral reef ecosystems, addressing specific problem areas related to reef degradation. Other predicted effects of global climate change, that may become evident during the next few centuries relate to (1) rapid sea level rise, which could cause reef submergence and increased erosion and sedimentation (Graus and Macintyre, 1998), and (2) increased CO_2 concentration that would decrease the aragonite saturation state in the world's tropical seas and thus reduce coral reef aragonite precipitation to perilously low levels (Kleypas et al., 1999).

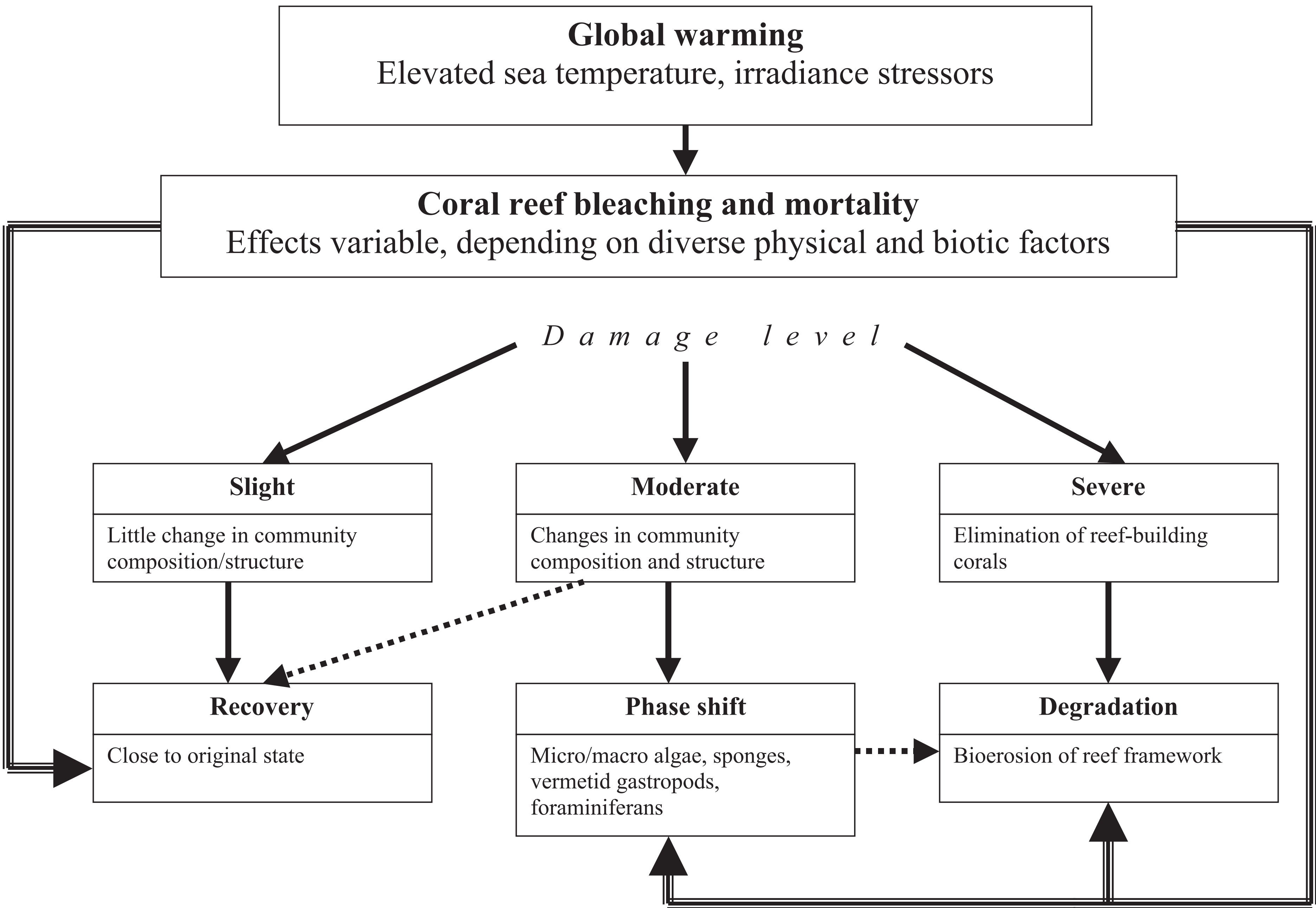
Attempts to define bleaching thresholds, such as "degree-heating-weeks" or "days", and more recently methods that take into account both the magnitude and duration of thermal stress (R. Berkelmans, in press), are advancing our understanding of coral responses to sea warming events. Because bleaching is so variable in space and time, it is imperative to continue studies of critical thermal thresholds, as well as species specific coral host and algal symbiont susceptibilities, not discounting the likely interactions of solar radiation, salinity, pollutants, and other stressors. While numerous population and community-level responses to bleaching events have been reported, these observations are often of disparate species and from different habitats and regions, making it difficult to develop a sense of generality, if such exists.

Even if bleached species survive and eventually recover, their populations will experience changes, often negative, relating to reproductive activities, fecundity, spawning rhythms, dispersal, settlement and recruitment. Such perturbations will inevitably result in changes to coral community composition and structure with alterations to interspecific and interphyletic patterns of competition, predation, symbiosis and disease. Such shifting community-level interactions will affect rates of calcification, framework building and carbonate accumulation. Bioeroder activities usually accelerate on reefs that have undergone large reductions in live coral cover, and carbonate erosion in the extreme can cause the fragmentation of reef structures, resulting in the loss of habitat complexity and reductions in biodiversity.

(See figure 1, next page)

With the likelihood that coral bleaching and mortality will increase on a global scale, it seems worth considering some special conditions under which corals are least impacted during periods of elevated sea warming. If some areas or habitats of relatively high coral survival exist, it would be useful to identify these and perhaps consider using this information in the design of marine proected areas (MPAs) to help mitigate the impact of bleaching events (Salm et al., 2000). A workshop

DECADAL SCENARIO OF WARMING EFFECTS ON CORAL REEFS



Glynn–2

convened at the Bishop Museum in Honolulu (29–31 May 2001), co-hosted by S. Coles, R. Salm and G. Llewellyn, identified several factors that seem to contribute to bleaching resistance and resilience. For example, some physical factors that appear to temper bleaching impacts are (1) water exchange, (2) upwelling, (3) location near deep water, (4) high current velocity, (5) shading, (6) turbidity, and (7) cloud cover. Resilience, or the ability of a disturbed coral reef ecosystem to return to its pre-disturbance structure and function, may be facilitated, for example, by (1) its connectivity with other coral reefs, (2) the availability and abundance of recruits and recruitment success, (3) diversity of symbionts and herbivores, and (4) low abundances of corallivores, diseases and bioeroders. By continuing to investigate such factors and their interactions, I am hopeful that present-day bleaching disturbances can be better understood, thus leading to effective conservation measures that could significantly minimize sea warming disturbances to some coral reef ecosystems.

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Graphics

1. *Changing views on the causes of coral reef degredation.*
A 1994 report on the Implications of Global Climate Change on Coral Reefs "...concluded that the major problems for coral reefs were direct anthropogenic stresses of nutrient pollution, excessive sediments and over-exploitation acting at many local sites near concentrations of people, and that global climate change was not yet an issue."

"Climate change by itself is unlikely to eliminate coral reefs...".

"Yet within 4 years of that report (1998), both authors have become convinced that evidence points to global climate change posing an equal or even greater threat to coral reefs than direct anthropogenic impacts."

C. Wilkinson,
Status of Coral Reefs of the World: 2000

2. *Factors Influencing Bleaching Resistance and Resilience*
Physical factors
- water exchange
- upwelling
- location near deep water
- high current velocity
- shading
- turbidity
- cloud cover

Biotic factors
- connectivity with other coral reefs
- availability and abudance of larvae
- recruitment success
- diversity of symbionts and herbivores
- low abundances of corallivores, diseases and bioeroders

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Bernard	Bill	3Di, Inc.	wbernard@3Dicorp.com	(410) 770-6001	(410) 820-5613	68969 Information Lane, Easton, MD 21601 USA	coral reef mapping and characterization with airborne hyperspectral instruments	2
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Mumby	Peter	University of Newcastle upon Tyne	p.j.mumby@ncl.ac.uk	44 191 222 6228	44 191 22 7891	Dept. of Marine Science - Ridley Bldg., The University of Newcastle upon Tyne, NE17RU, UK	reef remote sensing, MPAs	2, Leader
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Smith	Robbie	Bermuda Biological Station for Research	robbie@bbsr.edu	441 297-1880 ext. 240	441 297-8143	Bermuda Biological Station for Research, 17 Biological Lane, Ferry Reach GEO1, Bermuda	coral population biology, MPA fish recruitment, seagrass	3, Rapp.

Steneck	Robert	University of Maine, School of Marine Sciences	steneck@maine.edu	(207) 563-3146 ext. 233	(207) 563-3119	Darling Marine Center, Walpole, ME 04353 USA	community structure, monitoring AGRRA, plant/herbivore interactions, coralline algae, coral settlement	3
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Recognizing the importance of our living oceans to the future of mankind, the Khaled bin Sultan Living Oceans Foundation was established as a nonprofit, public benefit corporation to champion efforts towards conservation and restoration of living oceans and aquatic resources worldwide.

Khaled bin Sultan
Living Oceans Foundation

The Foundation pledges to join marine conservation efforts, increase public awareness, protect endangered marine species, facilitate access to remote marine sites, support scientific research, and build active partnerships among regional, national, and international organizations.

Graduate Fellowship in Marine Science

The Khaled bin Sultan Living Oceans Foundation has established a graduate fellowship for students interested in enhancing, protecting, and rehabilitating marine resources. The fellowship will provide a stipend and tuition for up to 36 months. Travel and research costs can, in some instances, be compensated.

Examples of Expeditions and Foundation-Sponsored Research Conducted in 2001

Often the most important research must be conducted at sites which are the most difficult to access. Since its inception, the Foundation has worked in partnership with the *Golden Fleet,* making several research vessels available to marine scientists from all over the world.

The fleet's logistical support yacht, the 67-meter *Golden Shadow,* is equipped with a complete marine laboratory, a diving recompression chamber, and a variety of tenders. The *Golden Shadow* also carries the *Golden Eye,* a ten-seat turboprop aircraft that can be fitted with a Compact Airborne Spectral Imaging System (CASI).

- **U.S. Virgin Islands**
  In April 2001, the Foundation sponsored research in the U.S. Virgin Islands. An extensive mapping of local reefs was conducted using CASI. This effort was led by Dr. Peter Mumby of the University of Newcastle in coordination with the U.S. National Park Service. An area of over 41,000 hectares was mapped, the largest analysis of its kind ever performed in the U.S.Virgin Islands. A baseline of data was developed, and new reefs were discovered.

- **The Mediterranean Sea**
  In June 2001 the Foundation supported an assembled team of scientists from Monaco, France, Canada and the United States, on an expedition led by Professor Jean Jaubert. The expedition covered an area in the Northwest Mediterranean from Toulon, in France, all the way to the French-Italian border. The team made extensive use of a CASI as well as using a spectroradiometer to profile light attenuation in the water column. By combining these two sources, the group was able to build a reference biotope database to analyze changes over time for the coastal shallow areas of the Mediterranean Sea.

- **Sea of Cortez**
  In February 2001, groups of U.S. and Mexican scientists joined forces in the Sea of Cortez off the coast of Mexico. Working on the *Golden Shadow*, the teams went to 12 different research sites, covering a distance of over 500 miles. The team was lead by Professor William Fenical from Scientists from the Scripps Institution of Oceanography, and Dr. Rosalba Encarnacion Dimayuga of the Universidad Autonoma De Baja, Mexico.

Visit our web site
www.khaled-livingoceans.org
for more about the Foundation
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Mission

The non-profit International SeaKeepers Society actively protects the oceans by equipping luxury yachts and other vessels and platforms around the world with sophisticated ocean and atmospheric monitors. These compact, high-tech monitors gather and transmit via satellite to the international scientific community critically-needed data on the health of the oceans, changing weather and climate patterns, sources of pollution and other threats to human life and marine resources.

Our Imperiled Oceans

Healthy oceans modulate the world's climate and provide food and economic sustenance for billions of people. They also present us with myriad opportunities for physical and spiritual renewal and inspire us with their beauty and their majesty. As we enter the 21st century, however, the oceans are imperiled. Vitally important food fish species are on the verge of extinction. Beaches and coastal areas are polluted. Toxic algal blooms threaten seaside populations. The oceans are rapidly losing their capacity to buffer us from potentially catastrophic climate changes. By embracing the International SeaKeepers Society, the yachting community is playing a front-line role in saving the oceans.

How pivotal is this role? The chief scientist of the National Oceanic and Atmospheric Administration (NOAA) has publicly commented that the SeaKeepers Society monitoring program "will revolutionize the way marine science is conducted in the future." NOAA has a formal agreement with the Society to distribute SeaKeepers data to weather forecasters, government agencies and ocean research institutes around the world.

NCORE

National Center for Caribbean Coral Reef Research

Science Advisory Committee

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NCORE

National Center for Caribbean Coral Reef Research

From Post-mortem Analysis to Useful Prediction

The National Center for Caribbean Coral Reef Research (NCORE) is a facility at the University of Miami dedicated to improving the scientific basis of coral reef management. NCORE is focused on advancing coral reef science to the degree that we can predict the consequences of a given disturbance or change in management strategy on the ecology of a coral reef and on reef-dependent people.

The Center's primary approach is to organize interdisciplinary research projects, pulling together highly effective international teams of scientists from the biological, physical, social and economic sciences. These teams will tackle key issues through tightly integrated field, laboratory and modeling investigations. NCORE has two main programs of research: 1) Reef Recruitment and Connectivity (RECONNECT), and 2) Comparative Analyses of Reef Resilience Under Stress (CARRUS).

The RECONNECT Program arises from the fact that most coral reef species undergo periods in early development of days or weeks in which they drift or swim freely amid ocean currents before settling in as "recruits" to a particular reef. The research integrates physical oceanographic modeling with studies of the genetic relationships among reef species across the region, and of the behavior and survival of the species before and after they settle. The effects of climate change on these processes are a particular concern, as a warming climate may lead to shifting currents, diminished recruitment, ecological changes and low fishery yields. The program has a regional focus, and has important implications for the management of reef fisheries, the design and deployment of protected areas, and the international cooperation necessary to ensure the longevity of coral reefs.

The CARRUS Program involves highly interdisciplinary, long-term studies on specific reef systems in support of the development and testing of predictive models and improved approaches to management and assessment. Focal areas include the coral reefs of the Florida Keys, Belize and the Bahamas. Remote sensing, modeling and field studies are used to determine the relationships among geomorphology, hydrography and ecology. The broad base of knowledge from prior research in these areas is being extended backwards across centuries through the analysis of ancient corals. Studies of the human dimension include analyses of the economics and quality of lives of reef-dependent people, of human impacts on the reefs, and of the consequences of the loss of reef resources to low-income people through depletion or restrictive management. The research centers around the development of 3-dimensional Geographic Information System – based Predictive Interdisciplinary Modeling & Expert Systems (GIS-PRIMES) designed to help policy makers and managers to predict the consequences of disturbances and management interventions on coral reefs and the people dependent on them.

NCORE collaborates in a variety of vital regional programs, including the MesoAmerican Barrier Reef System Project, the NSF Biocomplexity Program, the Atlantic & Gulf Rapid Reef Assessment (AGRRA) and the Caribbean Reefs at Risk Analysis. A series of high caliber workshops are being held, in order to summarize state-of-the-art knowledge and to prioritize research issues. On October 3–5, 2001, NCORE took the lead role in organizing the international workshop Research Priorities for Caribbean Coral Reefs, which involved 65 participants from 11 countries. Co-hosts included The Khaled bin Sultan Living Oceans Foundation and the International SeaKeepers Society. The results are posted at www.ncoremiami.org. NCORE was established by the U.S. Environmental Protection Agency as a Federal Demonstration Project in 1999, and receives supplemental funding from NOAA, NSF and a variety of other sources in the public and private sectors.

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NCORE

National Center for Caribbean Coral Reef Research

United States Environmental Protection Agency

The National Center for Caribbean Coral Reef Research (NCORE) was founded in response to the need for critical information on how to best assess and manage coral reefs of the Caribbean.

Located on the campus of the Rosenstiel School of Marine and Atmospheric Science at the University of Miami, the Center's primary focus is on the analysis and prediction of coral reef resilience. NCORE is conducting and developing interdisciplinary model-driven studies targeting key management issues relevant to this vital aspect of coral reef science. A major objective of the Center is to foster collaboration among research and management agencies, universities, non-governmental groups, international organizations and the private sector.