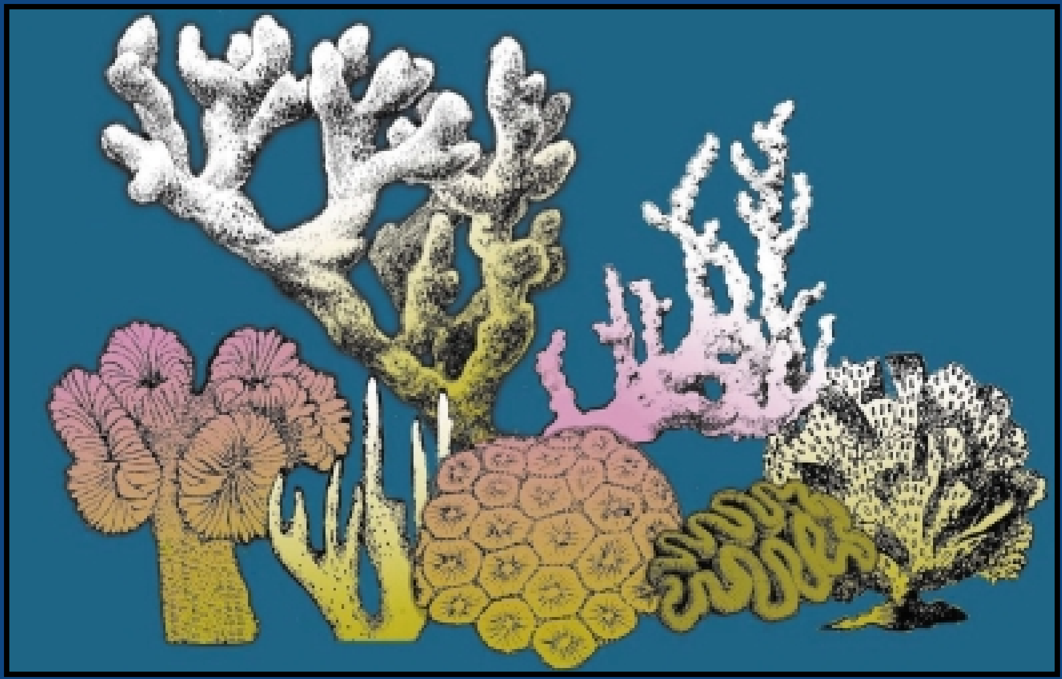
CORAL BLEACHING AND MARINE PROTECTED AREAS



Proceedings of the Workshop on
Mitigating Coral Bleaching Impact Through MPA Design
Bishop Museum, Honolulu, HI May 29-31 2001

SEPTEMBER 2001

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Steve Coles coordinated preparations for the workshop and production of this interpretation of the workshop deliberations. The diligence of workshop participants in preparing their contributions and the open spirit of dialogue and debate proved invaluable in exploring and refining the concepts under discussion and were critical to the successful conclusion of the workshop and quality of its outputs.

Shari Walker did a tremendous job of managing the workshop logistics—often-underestimated challenges that are vital to the effective execution of any workshop and the attainment of its objectives.

Rod Salm

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WORKSHOP SUMMARY

Those of us who knew the corals reefs of the world 30 years ago or more have seen widespread deterioration in their condition and in the numbers of fishes and mollusks they shelter. Projecting the past 30 years of change ahead another 30 years might be enough to drag us into a vortex of despondency. On the other hand, inspired by our conservation successes, we could rise to the challenge and look for solutions.

It makes good sense to prepare for what lies ahead in this new century by looking back at changes in the state of reefs and projecting these trends ahead to anticipate emerging threats. In doing so, we can position ourselves to be ready for them. Bleaching as a response by corals to stress caused by elevated seawater temperature is one of these emerging threats that has already led to the possible extinction of some coral species from reefs in the Panama and Okinawa regions, at opposite ends of the Pacific.

Mass coral bleaching of the scale following the 1998 El Niño Southern Oscillation (ENSO) event is viewed by some as an intractable problem and by others as a challenge we need to do "something" about. Patterns of bleaching in the Florida Keys National Marine Sanctuary show that each subsequent event has exceeded former thresholds of resistance and extended bleaching to new reefs. This is a matter of concern that increases the stakes and warns us that we cannot wait any longer to act. Responding to rising global concern, The Nature Conservancy (TNC) joined with the World Wildlife Fund U.S. (WWF-US) to determine how to shape the "something" into practical actions that could be implemented to mitigate the impacts of bleaching on coral reef biodiversity.

We convened a small working group of influential participants with significant experience in relevant coral reef research, monitoring, and marine protected area (MPA) management. Collectively, they embody comprehensive, direct knowledge of all major reef areas worldwide (Asia, Pacific, Indian Ocean, Caribbean, United States, and Australia).

The group was united and stimulated by a shared concept that, counter to the prevailing sentiment of doom and gloom, something ***can*** be done to address the severe impacts of climate related bleaching on coral reefs, even if sources of climate change are beyond our control within meaningful timeframes.

This first workshop was a determined attempt to explore and agree on some potential science-based principals that could guide management of current MPAs to mitigate the impacts of coral bleaching, optimize conditions for reef recovery, and steer the establishment of new MPAs. The intent was to build upon, not change, the many varied and excellent approaches to reef management by adding some complementary activities and approaches that are designed specifically to help managers address coral bleaching through mitigation strategies.

Hopefully, the workshop will catalyze a succession of other small, focused meetings aimed at determining how to control or mitigate other unmanageable global threats to marine biodiversity that are likely to emerge in this century. Examples of these include: sea level rise; increased demand for living space, food, materials, recreation, and tourism; habitat fragmentation and isolation; and accelerated introduction of invasive species.

The group confirmed a concept first developed by TNC that certain environmental factors favor survival or recovery of corals and other organisms which have bleached, and that policy-makers and resource managers should include reefs containing such factors within MPA networks. Also stressed was the need to assist the recovery of coral reefs that have bleached by protecting them from siltation, pollution, overfishing, and other destructive practices.

The group recognized that areas resistant to bleaching are critical to the recovery and survival of coral communities that succumb to bleaching or other stresses. If these resistant sites are not protected, they may be degraded by a host of other factors and lose their effectiveness as sources of larvae to enable the recovery of affected areas. Consequently, management should aim to protect areas of high resistance to bleaching, but protection should also be extended to enhance the recovery of adjacent areas by reducing the influence of other stresses. The group also found value in increasing the probability of reef community recovery from bleaching and other stresses through replication of MPAs—the more MPAs there are, the greater the likelihood that significant components of these will survive to facilitate recovery of affected areas.

The group agreed on a list of factors that confer bleaching resistance (coral colonies that don't bleach or bleach but don't die) and resilience (reefs where colonies bleach and partially or wholly die, but the coral community recovers). They outlined a general approach for a global program to test and verify that environmental factors are effective in mitigating bleaching impacts. The goal of this global program is to maximize the protection of coral reefs in the face of expected increases in frequency and intensity of climate related bleaching events.

Furthermore, the group agreed to work with MPA practitioners around the world to evaluate the vulnerability of existing MPAs to bleaching and the practicality of implementing the new management approaches. They recommended that additional criteria and principles linked to survivability should be considered alongside the widely accepted ones when selecting and designing new coral reef MPAs, but stressed the need to assist the recovery of bleached reefs by protecting them from other threats and managing them to promote resilience.

To derive all essential empirical data to support additional practices in MPA establishment and management could take up to a decade of research and monitoring. In the interim, there is value in using the best available information, both observational and available scientific data, to define MPA selection criteria, design principles, and management guidelines that can be updated and refined as the years go by. The ongoing research and monitoring also will be integral for developing an understanding of how to manage coral reefs in the face of global change.

The group agreed to proceed along a two-track approach. The first track includes worldwide assessments, research, and monitoring. These will be designed to provide solid scientific evidence to verify current information regarding the contribution of environmental factors to bleaching resistance and resilience. The reliability of these factors will be tested and applied to generate additional MPA selection criteria and design principles—the two primary components of the second track.

Simultaneously, through the second track, draft additional MPA selection criteria and design principles will be prepared and distributed globally for application, verification, and refinement. The IUCN World Commission on Protected Areas (WCPA) will play a key role in this process. The target is to assimilate feedback from the two tracks and present and discuss these additional MPA criteria and principles at the 5th World Parks Congress, to be convened by IUCN WCPA in mid-2003. A global MPA practitioners support network will be established during the Congress to facilitate global application of the new selection criteria and design principles.

Just as bleaching is not exclusive to a country or region and recognizes no institutional or national boundaries, neither is exclusion the intention of this two-track program, which would clearly benefit by implementation through a global partnership. TNC, WWF, and the workshop participants expressed firm commitment to build on this successful workshop and to collaborate to take this initiative forward in partnership with any other interested private or public organizations.

Rod Salm

INTRODUCTION

Both TNC and WWF have biodiversity conservation as the central pillar of their missions. Each organization is deeply concerned about the potentially severe impact of repeated mass coral reef bleaching that is linked to the El Niño Southern Oscillation (ENSO) events, and is striving to find ways to mitigate the related mortality and loss of biodiversity at scales that are meaningful in the face of widespread bleaching events. In that context, this meeting was convened to address the following problem: Is there anything that can be done to change the usual approach to coral reef conservation radically enough to influence coral reef survival at a global scale, despite mass bleaching?

When viewed from the perspective of reef management and conservation, these mass bleaching events are challenging, to say the least, and those who work in this field might feel powerless to act at scales that will make a significant improvement. One of us (Rod Salm) first started grappling with this challenge in 1990 while tracking coral bleaching in the Sultanate of Oman and continued in 1998 with the bleaching that hit Kenya and the Seychelles Islands. It was during his visits to Indonesia, Palau, and Papua New Guinea in 1999 and 2000 that patterns seemed to emerge. The literature contributed, too—not by the studies presented, but by those that were left out. Authors omitted certain sites from their studies, such as channels through reefs, because these showed low levels of or no bleaching, and consequently held little interest for their research.

Three things became apparent when considering ENSO-related bleaching. First, there appeared to be a collection of environmental factors that, working together or individually, could reduce the susceptibility of corals to bleaching and related mortality. This was interesting as it had the potential to enable predictions of where reefs or parts of reefs with one or more of these factors present would survive a bleaching event.

Second, ENSO-related bleaching shows little respect for MPA boundaries—even the most effectively managed MPA is vulnerable to coral bleaching and massive mortality. The implication of this is that we cannot rely on current methods of reef protection and management to bail us out of the bleaching crisis. This was recently underscored on Ngeruangel atoll in the far north of the island nation of Palau. The people of Kayangel State (all of whom live on one atoll) established Ngeruangel atoll, some seven miles away as a total reserve in 1996. Their own conservation officers patrol the area to keep out fishermen and other unauthorized visitors. Ngeruangel is remote. If there are any impacts of people on the reefs of the atoll, they are few and likely to be very minor. But the corals of Ngeruangel were highly impacted by the 1998 El Niño bleaching event, and there are huge fields of enormous staghorn corals in the atoll lagoon that remain dead and covered by sponges and algae. This is a perfect example of how a remote, well-protected area fell victim to bleaching.

Third, if indeed we can isolate environmental factors that render certain reefs or components of reefs less susceptible to bleaching-induced mortality and can demonstrate that these sites do survive subsequent bleaching events, we should be able to design our management to ensure adequate protection of these sites. For example, it should be possible to zone parts of larger MPAs, which have biodiversity conservation as an objective, to ensure high levels of protection for reef communities that consistently appear to resist bleaching, recover quickly, or have one or more environmental factors present. In some cases, luck rather than strategy or deliberate planning might already have assigned high levels of protection to the right places, such as the coral communities in Komodo National Park, which are influenced by cool water upwelling and mixing by strong currents. An understanding of these environmental factors and their role in bleaching resistance and resilience potentially adds another important piece to our scientific tools for selection, design, and management of MPAs. A global review of all coral reef MPAs to assess their management strategies in relation to coral bleaching should be considered as a follow-up to this workshop. Such a review should be conducted in concert with a review of other established considerations in MPA design, such as comprehensiveness, adequacy and representativeness, among others.

These ideas were presented during the 9th International Coral Reef Symposium in Bali to a group of both reef scientists and managers and received considerable encouragement from both. It is clear that people are concerned about what we can do to mitigate the impacts of ENSO-related bleaching on coral reefs at scales that are meaningful. The ICRS participants acknowledged that direct interventions are labor intensive, expensive, and very limited in scale for this purpose, and were receptive to the idea of using MPAs as a means to protect areas that survive or rapidly recover from coral bleaching. During the discussion following the Bali presentation, Billy Causey noted that there are discrete reefs in the Florida Keys National Marine Sanctuary that survive bleaching year after year and the fact that these sites receive no special levels of protection is an issue that needs to be addressed.

Protecting sites of low susceptibility to bleaching may not be enough. We also need to create conditions that enhance recovery of the susceptible areas. This means adequately controlling other stresses in the recovery sites to maintain conditions suitable for rapid recovery, and ensuring that that the resistant sites are upcurrent of the susceptible areas so as to enhance larval recruitment.

This leads us into the bigger picture of larval dispersal, recruitment, and the connectivity among reefs. Ultimately we must consider these factors in a global network of coral reef MPAs to ensure survival of representative biodiversity of coral reefs. A global network of interconnected reef reserves that are designed to survive and managed to be mutually replenishing is an admirable goal to pursue, even if the network will be completed and its success measured many decades after our lifetimes.

In summary, we are faced with the challenge of thinking at three different scales: 1) the local scale of different reef environments and habitats within MPAs; 2) the medium scale of factors and actors that can influence environmental conditions for recovery within a MPA; and 3) the distribution of MPAs at a global scale, with respect to global environmental and biodiversity patterns.

This workshop is just one step in the direction of determining what more it takes to design coral reef MPAs to survive. We should focus on practical, immediate measures that MPA practitioners can adopt. But we should be mindful of the larger context and longer time-scales that we must consider in order to establish a truly sustainable global network of coral reef MPAs. Once we have synthesized the most current thinking and information into a draft set of additional MPA selection criteria, design principles, and management guidelines, we will need to present these to a wider audience for global application, testing, and refinement.

Our approach focuses on confirming what, if any, predictable environmental determinants exist that would decrease the susceptibility of reefs or parts of reefs to bleaching related mortality. The approach also outlines an appropriate global research and monitoring program to test this possible relationship.

We propose that this approach should inform the definition of additional selection criteria, design principles, and management guidelines for coral reef MPAs to complement those that already exist.

We believe that changing the way we select, design, and manage MPAs can make the difference needed and we are committed to taking our outputs forward and promoting them around the world, together with any other willing partners.

Rod Salm and Ghislaine Llewellyn

Workshop Goal and Objectives

The goal of the workshop was to develop science-based principles to guide management of current Marine Protected Areas (MPAs) to mitigate coral bleaching and related mortality, optimize conditions for reef recovery, and guide establishment of new MPAs.

The Specific Workshop Objectives were:

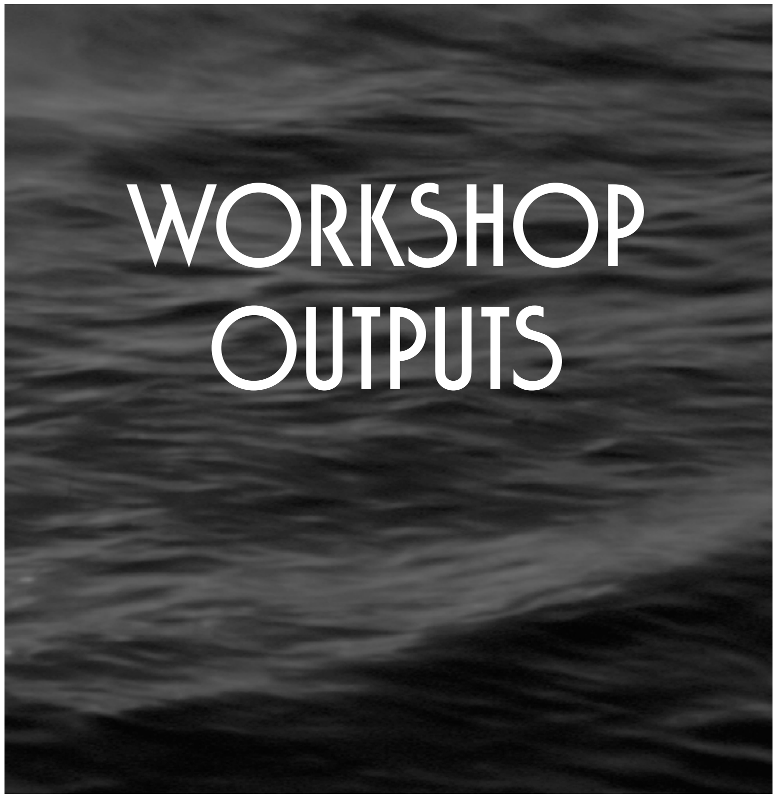
1. Agree on a list of environmental factors that potentially decrease the susceptibility of corals to climate-based bleaching and related mortality.

2. Agree on a range of monitoring methods and frequencies to test the hypothesis that MPAs can be used to mitigate coral bleaching and mortality through protecting sites where environmental factors favor coral survival.

3. Incorporate environmental factors that mitigate coral bleaching into draft MPA management guidelines and recommend additional selection criteria and design principles.

4. Devise a strategy for testing the hypothesis and draft MPA management guidelines at representative sites worldwide. These should include study site selection criteria, existing capacity for research implementation, presence of relevant environmental factors, and means for ensuring comparability of results.

5. Devise and recommend a strategy for implementing a global review of coral reef MPAs to test for the presence of environmental factors that provide protection from bleaching impacts and to identify sites with potentially high survivability in the face of bleaching that merit establishment as MPAs.


WORKSHOP
OUTPUTS

ENVIRONMENTAL FACTORS THAT CORRELATE WITH CORAL BLEACHING RESISTANCE AND RESILIENCE

Jordan West

Workshop Objective Relevant to Environmental Parameters (Objective 1)

Objective 1 *Agree on a list of factors that potentially decrease the susceptibility of corals to climate-based bleaching and related mortality.*

Such mitigating factors could operate by influencing the ability of coral colonies to resist coral bleaching mortality, or by enhancing the capacity of reef communities to regenerate (show resilience) after bleaching events.

Resistance

When mass coral bleaching and severe mortality occur, there is never total loss of all reef-building corals in any region. Instead, we see survivorship of scattered colonies, localized communities, or whole reef sections. These patterns of patchy survivorship often do not correlate with species-specific differences in bleaching tolerance but rather represent "pockets of resistance," where environmental conditions seem to boost the capacity of corals to resist bleaching mortality during and after mass bleaching events. For the purposes of this workshop, then, the term *resistance* refers to the ability of individual corals to either resist bleaching, or to successfully recover after they have been bleached. Such resistance may be due to either or both of the following: 1) intrinsic, species-specific physiological tolerance; 2) extrinsic environmental factors that afford some (but not necessarily full) protection from bleaching conditions, such that a subset of corals has a higher probability of surviving bleaching events. In the case of condition 1, our use of *resistance* corresponds with Done's (1999) use of "tolerance" to describe persistence in the face of disturbance such that there is no change in longevity of individual corals (although sub-lethal bleaching may occur). Condition 2 extends our definition of *resistance* to mean that certain localized environmental factors can sometimes boost resistance of the local coral assemblage, whether or not the individual corals have any intrinsic physiological tolerance. In other words, resistance also means environmentally provided (extrinsic) "tolerance" in the form of partial protection from bleaching events.

Resilience

After mass coral bleaching has occurred, resulting in associated mortality of a subset of coral colonies in a community, coral reef systems can differ in their *resilience*, or ability to return to their previous state of diversity and abundance. Nyström *et al.* (2000) discuss resilience in terms of the speed of return to equilibrium after a disturbance and the magnitude of disturbance that can be absorbed by a system before it shifts from one stable state to another. Thus, coral reef resilience can be characterized by the ability of reef communities to regenerate to their former state through growth and reproduction by surviving corals and through successful larval recruitment from within the area or from adjacent areas. The environmental conditions that favor such determinants of community resilience may be different from those that favor resistance. Resilience is an attribute of the site, i.e., the extent of the "ecological legacy" demonstrated by number of survivors, availability and settlement of coral larvae, and growth of survivors and new recruits

Factors that Correlate with Bleaching Resistance

A variety of physical and biological factors and phenomena have been observed to correlate with enhanced resistance to coral bleaching and mortality in the field. Done (this volume) noted that an ideal configuration of MPAs would include a full suite of regional biodiversity in areas that display a "tolerance" (i.e., resistance) to climate-related stress. Indicators of this may be areas that are known to have survived an earlier bleaching event, or areas with good cover of older corals. Glynn (this volume) reviewed data from the eastern Pacific region and concluded that habitats most likely to be least damaged during bleaching events include upwelling areas (with cooler water), deep areas (with reduced light and temperature), and areas of rapid current flow (which flushes harmful bleaching toxins). Also included are areas that are nearshore (where water clarity allows penetration of harmful solar radiation, and temperature changes during ENSOs are more extreme relative to normal conditions).

West (this volume) surveyed the literature and compiled observations from the Coral-List Listserver (www.coral.noaa.gov) to develop four main categories of indicators of resistance to coral bleaching: 1) upwelling of cool water, 2) water movement, 3) protection from solar radiation, and 4) habitats with a history of exposure to stress (such that those coral communities are pre-adapted to stress). These categories incorporate a variety of conditions that favor resistance. West also noted that the factors of greatest interest and usefulness to managers will be those that are reliable (predictably present) and persistent during bleaching events.

Starting with the above conceptual analyses, the workshop participants discussed and refined an expanded list of factors that could potentially predict coral bleaching resistance (Table 1). These are divided into a variety of physical factors that enhance resistance by reducing temperature stress, by enhancing water movement that flushes harmful bleaching products, or by decreasing light stress. Another category of factors includes those that may favor pre-adaptation of corals (i.e., biological tolerance) to coral bleaching due to the presence of regularly stressful environmental conditions. Further, each factor is categorized as "High" or "Low" priority for use as a selection criterion or indicator of likelihood of survival, based on whether the factor is considered to be reliable in its presence and persistent through time, especially during periods when climatological conditions favor bleaching events.

Table 1. Agreed list of factors that may correspond with coral bleaching resistance. Priority level indicates degree of reliability as a predictor of coral survival.

RESISTANCE FACTORS	PRIORITY
Physical Factors that Reduce Temperature Stress	
• Exchange (warm water replaced with cooler oceanic water)	High
• Upwelling	High
• Areas adjacent to cooler deep water	High
• Wind-driven mixing	Low

Table 1. (Cont.)

RESISTANCE FACTORS	PRIORITY
Physical Factors that Enhance Water Movement and Flush Toxins	
• Fast currents (eddies, tidal and ocean currents, gyres)	High
• Topography (peninsulas, points, narrow channels)	High
• High wave energy	Low
• Tidal range	Low
• Wind	Low
Physical Factors that Decrease Light Stress	
• Shade (high island shadow, reef structural complexity)	High
• Aspect relative to the sun	High
• Steep slope	High
• Turbidity	Low
• Cloud cover	Low
Factors that Correlate with Bleaching Tolerance	
• Temperature variability	High
• Emergence at low tide	High
• Broad range of coral colony size and species distributions	High
• Areas of greatest remaining coral cover	High
• Stable salinity	High

Factors that Contribute to Coral Community Resilience

Resilience factors are conditions that boost the capacity of coral reef communities to recover after bleaching mortality events. They operate by enhancing reef regeneration through re-colonization and regrowth. Glynn (this volume) noted that upwelling areas and deep areas exhibited enhanced recovery after bleaching events in the eastern Pacific, and that this was presumably due to some environmental factors that favored resilience in those habitats. Done (this volume) emphasized the importance of targeting for MPA inclusion strategic locations that maximize both strong and reliable recruitment of all species within the community and the likelihood that a portion of the propagules from those communities will effectively seed other areas.

The workshop participants concluded that resilience factors operate at levels that are both intrinsic and extrinsic to coral communities. For instance, some resilience factors relate to the intrinsic ability of corals to produce larvae that will recruit successfully. Other factors intrinsic to communities have to do with whether ecological conditions on a reef favor survivorship and growth once the recruits arrive – this might include well-balanced diverse communities with low abundance of bioeroders, corallivores and diseases. Finally, there are extrinsic, regional-scale physical factors to consider, such as current patterns that may favor larval dispersal and connectivity among sites. Based on the above, the group developed a list of resilience factors and categorized each as high or low priority depending on the degree of predictability and reliability (Table 2).

Table 2. Agreed list of factors that may contribute to coral community resilience. Priority level indicates degree of reliability as predictor of coral survival.

RESISTANCE FACTORS	PRIORITY
• Reef connectivity by currents	High
• Availability and abundance of recruits and recruitment success	High
• Diverse community of organisms to prepare substratum for coral settlement (e.g. herbivorous fishes)	High
• Low abundance of bioeroders, corallivores, and diseases	High
• Good potential for recovery because of effective management	High

Factors that Need Verification and May Not Be Immediately Applicable

Participants discussed a wide range of factors currently under study and techniques being developed to detect and quantify bleaching impacts. These may prove to have important roles in the future, but were considered to be of low applicability for this project. These factors include:

- Colony morphology
- Colony growth rate
- Genetic differences among corals
- Genetic differences among zooxanthellae
- Fluorescent pigments
- Light variability
- Nutrients
- Light absorption by chromophoric dissolved organic matter (CDOM)
- Influence of dissolved oxygen levels

Development of Questionnaire to Assess Environmental Factors That May Contribute to Coral Bleaching and Resilience

Following the discussion of agreed factors of resistance and resilience, the group agreed to develop a questionnaire for rapid assessment of what is currently known by managers about these factors and their effects on coral reefs in every region, both inside and outside of MPAs. The questionnaire is designed to collect basic information on environmental factors and coral condition, wherever such information is available from local managers, in a format that will allow multivariate analysis. The analysis will determine the significance of the different factors in influencing coral condition, plus, where possible, the significance of MPAs in influencing the operation of the factors. From this preliminary analysis may emerge some factors that are of clear importance to coral bleaching resistance and resilience. Managers could begin immediately using these factors as indicators of where management efforts might best be focused for preservation of coral reef biodiversity in the face of continuing climate-induced bleaching.

Besides providing a method for preliminary testing of hypotheses related to the effect of different factors on coral bleaching resistance and resilience, the questionnaire will also provide information on good potential candidate sites for further targeted monitoring (see monitoring section below). Sites with a variety of reef types, both within MPA areas and in control locations outside of MPAs with some kind of monitoring program already in place, may be considered candidate sites for further research. At these sites, additional detailed monitoring could be implemented to test specific hypotheses about the reliability, persistence, and significance of each individual factor. This longer term, targeted monitoring program would involve data collection before, during and after the next climate-related bleaching event.

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MONITORING THE ROLE OF ENVIRONMENTAL FACTORS IN MITIGATING BLEACHING DAMAGE ON CORAL REEFS

Steve Coles

Workshop Objectives Relevant to Monitoring (Objectives 2 And 4):

Objective 2 *Agree on a range of monitoring methods and frequencies to test the hypothesis that MPAs can be used to mitigate coral bleaching and mortality through protecting sites where environmental factors favor coral survival.*

Objective 4 *Devise a strategy for testing the hypothesis and draft MPA management guidelines at representative sites worldwide. These should include study site selection criteria, existing capacity for research implementation, presence of relevant environmental factors, and means for ensuring comparability of results.*

In addressing these objectives the workshop participants concluded that it is essential to first verify the role and reliability of environmental factors in conferring resistance and resilience to coral communities subject to bleaching. This section outlines a plan for monitoring to evaluate the effectiveness of environmental factors in helping coral communities resist or recover from coral bleaching. While not advocating any particular monitoring technique, we focus on parameters to be measured and appropriate frequency of monitoring for background conditions, at the time of a bleaching event and during recovery.

Capacities for coral reef monitoring vary widely around the globe, and a range of methods has been successfully used to monitor reef condition. The intention is to utilize the information from existing programs wherever possible, and to propose modifications that may make the these programs more amenable to evaluating the long-term effects of coral bleaching.

General Approaches to Monitoring

The general requirements of a program to monitor bleaching impacts are: 1) it uses consistent techniques with sufficiently high resolution to detect significant changes in coral cover and composition; 2) the data obtained are amenable to statistical analyses and can be stored in a variety of media; and 3) the data are accessible at a future date for comparing with conditions existing at that time.

A monitoring program should be long-term in scope and include four major components:

1. Baseline Conditions

The baseline conditions and characteristics of a reef should be determined during an initial rapid assessment survey. In addition to physical and biological components measured or evaluated at the time of the survey (Table 3), all information available for the site from long term records—such as tide and temperature data—should be utilized.

2. Background Variability

Physical and biological parameters (Table 3) should be monitored at least annually before and after a bleaching event to sufficiently establish baseline conditions. These surveys should be conducted during or in the first month after the annual temperature maximum.

3. Rapid Response and Recovery

An early warning and response system will need to be developed to enable trained monitoring teams to track bleaching events and determine bleaching impacts on reef communities. The warning system could consist of local observers, such as tourism operators and fishermen, and links to remote sensing technology such as the NOAA "HotSpots" email notification system. When the onset of a bleaching event has been identified, a monitoring team should be mobilized rapidly to repeat the standard set of monitoring measurements. Rapid response teams should include members that perform annual background monitoring and, wherever possible, researchers conducting more specialized measurements of coral bleaching related factors (e.g. zooxanthellae genetic composition and fluorescent pigments), if available.

The first rapid response survey should conduct the standard set of monitoring measurements at the time of the initial bleaching event. That should be followed by three more surveys by the monitoring team, at approximately one and three months after the onset of bleaching and at four to six months after the conclusion of the bleaching event. In addition to the standard measurements, extra observations are encouraged during recovery surveys. Such information includes condition of bleached colonies tagged during the initial rapid response survey, number and colony size of recruits, incidence of disease, and succession in the principal component organisms of the benthic community. Following this series of recovery surveys, annual monitoring will be considered part of the long-term recovery phase, and these measurements should continue to be emphasized.

This monitoring program will: 1) require a time frame of 10 years in order to effectively establish baseline conditions, 2) include at least one major El Niño-based bleaching event, and 3) determine rates and conditions of recovery or change in reef communities following bleaching.

Table 3. Parameters selected by workshop participants and ranked for their potential effectiveness in mitigating coral bleaching impacts.

	PARTICIPANT											
Parameter	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**Rank**
Initial Assessment:												
Ecological Context/Characterization		*		*	*	*	*	*	*	*	*	1
Depth	*	*	*	*	*		*		*	*	*	1
Slope	*	*	*	*	*		*		*	*	*	1
Habitat Classification (Fringing, barrier, patch reefs)			*	*	*	*	*		*	*	*	4
Regional Oceanography		*	*			*	*	*	*	*	*	4
Longitude/Latitude	*	*	*	*	*		*		*		*	4
Topographic Maps		*			*		*	*	*		*	7
Rugosity			*		*				*	*	*	8
Sediment Composition							*			*	*	9

Table 3. (Cont.)

Parameter	PARTICIPANT 1	2	3	4	5	6	7	8	9	10	11	Rank
Aerial Photographs	*										*	10
Remotely Sensed Historical Data	*										*	10
Anecdotal/Published Local Historical Information	*										*	10
Monitoring Phases												
Physical Parameters (with appropriate calibrations)												
Temperature	*	*	*	*	*	*	*	*	*	*	*	1
Water Motion		*	*	*			*		*	*		2
Turbidity				*	*			*	*	*		3
Light Variability		*		*				*				4
Biological Parameters												
Coral Condition:												
"Normal," "Partially Bleached," "White," etc.	*	*	*	*	*	*	*	*	*	*	*	1
Benthic Cover by Category and/or Lowest Poss. Taxa	*	*		*	*	*	*	*	*	*	*	2
Presence/Abundance of Key Functional Trophic Groups		*		*			*	*	*		*	3
Quantitative Size Distributions by Coral Species		*	*	*			*	*				4
Coral Recruitment Rates		*		*			*	*	*			4
Fish Species, Number and Biomass		*			*			*			*	6
Census of Coral Species					*			*		*		7
Bioeroder Densities								*			*	8
Zooxanthellae Densities and Chlorophyll Concentrations								*	*			8
Presence/Abundance of Fluorescent Pigments		*										10
Coral Diseases				*								10
Zooxanthellae Genetics								*				10

Measurement of Parameters

1. Initial Assessment

The purpose of an initial assessment is to establish baseline conditions from which future changes can be evaluated. At a minimum, this assessment should include measurements of physical parameters (such as reef depth, slope and rugosity, water clarity and motion, and tidal range) and characteristics of the reef community (including coral cover and species composition, dominant macroalgae, prominent macroinvertebrates, and fishes). Available supplementary information from available maps and bathymetric charts, oceanographic atlases, regional databases and aerial photographs should be utilized to characterize the ecological context of each site as completely as possible.

Monitoring Phases

Measurements to be utilized in periodic background monitoring and rapid response and recovery surveys include both physical and biological parameters.

Physical Parameters. Information summarized in the Environmental Factors section of this paper indicates that temperature, water motion, and light intensity are primary factors in determining coral bleaching and its long term impact. Measurement of these parameters is basic and essential for determining whether environmental factors can contribute to bleaching resistance or resilience.

Temperature should be measured continuously using *in situ* data loggers in areas of active coral growth and spot-checked at times of surveys using calibrated thermometers. Temperature loggers should be deployed in arrays extending from the reef flat to the base of the reef slope to define the long-term temperature depth profile for a given site. Where *in situ* temperature loggers are unavailable for deployment, measurements should be made as frequently as possible using a calibrated thermometer.

Ideally, water motion should also be measured on a continuous basis using recording current meters, which also can continuously record water temperature. However, where instrument cost is prohibitive, valuable information on water motion can be obtained using plaster of Paris "Clod Cards" (Jokiel and Morrissey 1993) calibrated against known rates of water movement. Short-term advective water motion can also be inexpensively measured using drifting current buoys and dye flow determinations.

Continuous *in situ* measurement of light conditions at depth on a reef is problematic, since suitable recording instruments are not available at a realistic cost. The usual approach is to utilize surface light recorded at the meteorological station operating closest to the site, then estimate light conditions at depth using spot measurements of light differences or attenuation with depth. Relative differences in light conditions at depth can be roughly estimated by using a diver-held photometer at various spots and depths in the area or by pairs of divers making underwater horizontal Secchi disk observations, provided cloud cover is absent or constant. If an instrument is available, light attenuation should be measured using surface and at-depth photoreceptors during reef surveys. For turbidity determinations, water samples can be taken for later turbidity measurement in a nephelometer. Even if no equipment is available for quantitative measurements, observations of light conditions and water clarity (e.g., "full sun" vs. "shaded," "turbid" vs. "clear"), or estimates of underwater visibility in standard increments (e.g., 0-5 m, 5-10 m, 10-15 m, >15 m, etc.) will provide valuable information for evaluating conditions regarding a bleaching event and recovery.

Biological Parameters. The primary biological factor to monitor is coral condition, starting with basic observations of coral pigmentation in categories of "normal," "partially bleached" or "pale," "fully bleached" or "white," and "dead". Such observations are subjective, and methods are under development for more objective standards utilizing standard color charts or photographic/computer analysis techniques (Maguire *et al.* 2000; Marshall *et al.* 2001). Where possible and the means of analysis available, samples should be taken for pigment extraction and/or zooxanthellae density counts to establish objective measurements of the state of bleaching and recovery.

Each monitoring survey should include quantitative measurements of coral cover and condition using a consistent methodology for estimating benthic cover. Identification of corals at least to genus is highly desirable, but can be limited to listing by major growth form and total cover. Benthic cover determinations should include macroalgae and macroinvertebrates, especially colonial forms such as sponges, bryozoans, and ascidians that may compete with corals for space on the reef, especially after a stress event such as bleaching. These data, along with estimates of fish densities and populations, will be used in establishing key functional trophic groups, especially herbivorous fish and macroinvertebrates which consume algae that may compete with corals in the recovery phase following a bleaching event.

Recommended techniques for conducting the surveys will be developed in a separate document. However, a number of resources are available that summarize coral reef monitoring approaches at various levels of resolution and effort. Basic methods of coral reef monitoring that summarize the approaches used by ReefCheck and the Global Coral Reef Monitoring Network (GCRMN) are presented in the interactive CD-Rom C-NAV, and the standard GCRMN methodology is presented in detail in English *et al.* (1997). A rigorous analysis of various coral monitoring methods and the approach chosen for the Hawaii Coral Reef Monitoring Program (CRAMP) is available at the CRAMP website (http://cramp.wcc.hawaii.edu/Overview/3._Methods/). Monitoring methods that have been used in the U.S. Virgin Islands are given in the Coral Reef Monitoring Manual for the Caribbean and Western Atlantic (Rogers *et al.* 2001). A variety of resources for coral reef monitoring are listed on the Coral Health and Monitoring Program (CHAMP) website (http://www.coral.noaa.gov/methods.html).

Hypothesis Testing

Hypotheses chosen to test the effectiveness of environmental factors in conferring resistance or resilience of reefs to coral bleaching are listed in Table 4. These would be tested using the data acquired from the initial assessment of each site's environmental factors and from the subsequent monitoring program results.

Table 4. Hypotheses to test effectiveness of environmental factors in conferring coral bleaching resistance or resilience

	Factor Confers:	
Hypothesis:	**Resistance**	**Resilience**
Proximity to deep cooler water	X	
Windiness	X	X?
Locally high (> 1.5 m) tidal amplitude	X	
Areas with good mixing and fast currents	X	X
Areas with high wave energy	X	
Areas on points, promontories, channels	X	
Areas in deep shade from high land	X	
Areas with high structural complexity	X	
Areas with pole facing aspect	X	
Areas with high turbidity	X	
Areas with high cloud cover	X	
Areas with steep slope	X	
Areas with high temperature fluctuation	X	
Coral emergent at low tide (shallow reef flats)	X	
Areas with high recruitment rates		X
Areas with abundant grazers		X
Areas with low abundance bioeroders		X
Areas with low abundance corallivores		X
Areas with low abundance of coral disease		X
Areas with strict protection	X?	X
Areas not subject to salinity extremes	X	X

Multivariate analyses could be conducted testing the effectiveness of these factors both within and outside of MPAs, to determine whether establishment of MPAs is any more effective in ameliorating coral bleaching than areas outside of MPAs with similar characteristics. Potential dependent variables would be severity of coral bleaching, short to mid-term coral mortality, decline/recovery of coral communities, changes in herbivore populations, and phase shifts to alternative dominant reef communities. After five years of monitoring, these analyses would be appropriate for reconsidering the variables being surveyed and the processes involved, and after ten years for evaluating the entire program.

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LOOKING FORWARD: GLOBAL ACTION PROGRAM

Rod Salm and Ghislaine Llewellyn

Progress to Date

The original goal of this initiative was to provide managers with science-based guidelines to help mitigate bleaching impact on reefs and to formulate policy recommendations that would incorporate bleaching as a significant threat to reefs globally. This concept was met with overwhelming support when presented at the 9th International Coral Reef Symposium in October 2000. Scientists and managers voiced an urgent need for solid, science-based, practical guidance to help tackle the threat of mass coral mortality due to bleaching, and for a framework for a more systematic study of its impacts and the recovery process. As the next step in moving the initiative forward, TNC and WWF brought together a group of scientists, conservationists, and practitioners to a small workshop in Hawaii in May 2001.

The workshop participants recognized the need for a global program to test the hypotheses linking the list of environmental factors to bleaching resistance and resilience, and they are confident that MPAs can play a significant role in protecting coral communities influenced by these factors. The participants agreed that such a program would necessarily be long term (ten years minimum) and would need to be implemented through the collaboration of partners around the world. Nonetheless, they acknowledged that sufficient scientific and observational evidence exists to support some immediate action, at least on a trial and adaptive basis.

Critical components of this global program are discussed below and form the major thrust of immediate program implementation.

Concept Communication and Outreach

Following the 9th Coral Reef Symposium and the May 2001 workshop, a series of products are immediately available to interested scientists, MPA managers, and policy makers.

Ninth International Coral Reef Symposium Paper: A paper presented during one of the coral bleaching sessions at the Symposium, which describes the general goals and concept of this program, was recently published in a collection of bleaching-related papers from the symposium (Salm *et al.* 2001). The paper also has been submitted for publication in the symposium proceedings.

Post Workshop Publications and Presentations: As an immediate ongoing activity, the May 2001 workshop outputs are being summarized and communicated through various media. These will include newsletters of scientific and resource management societies, at least one peer-reviewed journal and similar publications, and a workshop proceedings publication with two stand-alone volumes—one a manual to help measure the role of environmental factors in coral resistance and resilience to bleaching and the other on the policy applications of the workshop output. In addition, the workshop findings will be communicated through a series of presentations in different forums and as the opportunity arises. Key in this process will be the IUCN/WRI Climate Change: Coastal Adaptation Partnership that meets in Washington DC to discuss specific actions that can be taken to address climate change impacts on the marine environment. Another important venue includes the meetings of the U.S. Coral Reef Task

Force. Responsibility for development of these written and presentation materials will be shared among all workshop participants to the extent permitted by their work programs. TNC has undertaken to produce materials for the IUCN 5th World Parks Congress in 2003.

This process of outreach will help to identify willing program partners who will assume responsibility for implementation of activities at different geographic scales, both site-based and analytical.

Program Development and Fundraising

TNC, together with WWF and the Bishop Museum, and with the input and support of workshop participants, will develop a program document consisting of separate modules for various components of the program. The document will serve to facilitate coordinated fundraising and program implementation. It is envisioned that partners will implement the program, possibly under the umbrella of a coordination committee comprised of selected workshop participants and other interested parties. Defining this structure will be a primary task of the workshop follow-up activities.

A program of this scope will be unprecedented in coral reef science and management. Since it deals with a problem both worldwide and long term, it will require substantial and reliable funding over a minimum ten-year period in order to select candidate reef sites, establish MPAs, conduct monitoring, and evaluate results. Fundraising would be the individual responsibility of program partners. However, partners in a position to raise funding for more than the specific areas of their immediate interest should do so. TNC is committed to working with partners to raise funding for the global program.

Initial Assessment Of The Influence Of Environmental Factors On Bleaching Resistance And Resilience

The initial assessment will be implemented through a questionnaire that has been designed to enable rapid collection of data on the relative impact of bleaching at different reef sites and a preliminary but systematic analysis of bleaching in relation to the agreed environmental factors. This questionnaire will be part of a comprehensive vulnerability assessment framework to assess the impact of bleaching on reef systems, but can also stand alone as a rapid assessment tool to review impacts on individual reef sites.

After testing and refining the questionnaire at a few pilot sites, it will be distributed in hard copy to some of the more remote reef areas of the world and will be posted in electronic form on the ReefBase web site for more global accessibility (Appendix 3). The questionnaire includes the environmental factors that were developed during the workshop and invites responses in a format that can be readily utilized for a multivariate analysis of the relative contributions of these factors to bleaching resistance and resilience. The analysis, which will be undertaken by the Australian Institute of Marine Science in conjunction with ReefBase, will also help to identify the most appropriate research and monitoring sites for more vigorous testing of the effects of the different environmental variables on coral bleaching resistance and resilience.

TNC and WWF will complete these questionnaire surveys at their project sites and assist partner organizations in doing so for other sites, wherever possible. Potential partners with representatives at regional nodes, such as the Global Coral Reef Monitoring Network, will be invited to catalyze completion of questionnaires, to establish and maintain communication between reef managers and scientists in the field, and to collate and disseminate information relevant to the program.

MPA Selection Criteria, Design Principles, And Management Guidelines

As a companion volume to this workshop report, draft additional MPA selection criteria, design principles, and management guidelines will be prepared and widely disseminated through regional and global networks. The IUCN World Commission on Protected Areas provides a key opportunity for this. The intention is that these draft criteria, principles, and guidelines will be tested and refined by program partners at different MPA sites around the world. They will be further revised using feedback from the MPA sites and the initial questionnaire assessment, and will be presented for discussion at the IUCN 5th World Parks Congress in 2003. The need for a global support network for MPA managers wishing to apply these criteria, principles, and guidelines at their sites will be floated at the Congress and, if seen to be in popular demand, steps will be defined for network establishment and operations.

Vulnerability Assessment

The mass bleaching events of 1997-1998 showed that climate change is a significant additional threat to the health and integrity of coral reef ecosystems that are already subjected to multiple chronic stresses. To understand the possible long-term consequences of climate change stresses, at both regional and local scales, a vulnerability assessment framework will be drawn up that allows a systematic analysis of past and future responses of reef systems to mass bleaching events. The goal will be to determine which reef systems, or component parts, may be least vulnerable to mortality from bleaching and act as important long-term refugia of coral reef communities.

The first step will be to isolate and identify the reef systems for analysis. These reef systems will be large scale (covering hundreds to thousands of square kilometers) and will include areas such as the Meso-American Barrier Reef, Great Barrier Reef, the Hawaiian Islands, the Fiji Reefs, the Maldives, Seychelles, the Red Sea, and so on. These systems will be analyzed using combinations of historical and contemporary information to determine their responses to global bleaching events. For example, do these areas experience bleaching or not? If not, what are the possible explanations for the lack of bleaching response that can be derived from geographic location in the context of prevailing climatic and oceanographic conditions?

The second step will be to determine the susceptibility to bleaching of reef components within the larger system and to reconcile any differences with the list of environmental factors used in and refined by the initial questionnaire assessment. Again, this analysis will require the input of a combination of historical, recent, and contemporary data, including responses to the questionnaire assessment.

The third and final step will be to process the information from the preceding two steps and identify reef systems with higher or lower survival prospects in the face of coral bleaching. These areas will then be reviewed for the adequacy of coral reef conservation measures implemented there. This step will lead to recommendations for increased MPA establishment and improved MPA management both in reef systems that demonstrate low vulnerability to bleaching and at specific reef sites within these systems with high resistance and resilience to coral bleaching.

WWF-US has indicated a strong commitment to lead this process.

Global Research And Monitoring Program

A range of research and observations supports our premise that environmental factors can be effective in helping coral communities resist or recover from bleaching. If the premise is upheld by focused research, its implications could be potentially wide-ranging for future coral reef MPA selection, design, and management. However, before advocating any changes in the way MPAs are viewed, selected, and managed, we must obtain convincing empirical data to support the role of environmental factors in safeguarding corals from bleaching or enhancing their recovery. The deliberations of the workshop and the initial questionnaire assessment will provide us with sufficient evidence to act now and initiate some change, particularly in affording strong protection to areas that regularly survive bleaching events. But change on a global level will need more substantive evidence, which the process outlined below is designed to explore over a period of ten years.

There are three steps to this global program of research and monitoring. The first is to implement annual background monitoring on coral reefs both inside and outside MPAs. This monitoring will provide the baseline data from which to determine normal levels of variability in specific physical and biological parameters. In turn, the baseline will provide the standard against which to measure change caused by bleaching. Implementation of this monitoring will depend upon participation by a wide range of program partners.

The second step is to develop and implement an early warning system to alert program partners of an impending bleaching event predicted from patterns and movements of seawater hot spots. The NOAA Sea Surface Temperature and Coral Bleaching HotSpots website provides the data at (http://orbit-net.nesdis.noaa.gov/orad/sub/key_sst_50km_field.html), which is available to those with affordable internet access. ReefBase will relay this information to program partners without access.

The third step is to implement rapid response research and monitoring to track the impact of bleaching on study reefs (mortality and recovery as measures of resistance and resilience, respectively), and to determine what role MPAs can play in aiding the recovery of affected communities. Program partners will carry out this step, relying, where necessary, on a support team of researchers that can mobilize rapidly to help implement the research.

The annual background monitoring will continue following a major bleaching event to monitor the recovery process for affected reef communities and provide insights into practical MPA management responses to these events.

Policy Application

The envisioned output of the process outlined above is a synthesis of data that will convincingly demonstrate what action, if any, can be taken to mitigate the impact of coral bleaching though MPAs, and how to go about it. Three anticipated products with potentially wide-ranging policy application include:

1. Additional MPA selection criteria, design principles, and management guidelines that integrate the survivability factors with others relating to biodiversity, aesthetics, tourism, fisheries, etc. that could substantively change approaches to coral reef conservation and secure their survival in the face of global climate change.

2. A global assessment of all coral reef systems and MPAs that demonstrates the vulnerability of these to climate-related bleaching. The assessment will identify reef systems and specific sites with high bleaching resistance and resilience that are underrepresented in MPAs and where future investment in MPA establishment is required. It is anticipated that this assessment document will substantially redirect coral reef MPA activity towards the priority reef systems and sites that it identifies.
3. Long term amelioration of the worst impacts of coral bleaching achieved by selection, design, and management of MPAs using the principles developed from this program. Implementation of this program on a worldwide basis represents one practical approach to address the degradation of coral reefs anticipated from widespread coral bleaching.

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KEYNOTE
PAPERS

Coral Bleaching: What Do We Know And What Can We Do?

Steve L. Coles[1]

Introduction

Coral bleaching, or the separation of coral algal symbionts (zooxanthellae) from a host coral, is a process that was first described over 75 years ago (Boschma 1924; Yonge and Nicholls 1931a; Yonge and Nicholls 1931b), but which has become a pervasive and frequent phenomenon over the past 20 years (Glynn 2000; Wilkinson 2000; Wellington *et al.* 2001). The interruption of vital functional relationships between corals and their zooxanthellae that occurs with bleaching is considered symptomatic of various stresses (Yonge and Nicholls 1931a). When stresses are prolonged or extreme, bleaching leads to mortality of the coral host (Glynn 1984; Lasker *et al.* 1984; Fisk and Done 1985; Harriott 1985; Oliver 1985; Brown 1987; Glynn 1989; Brown and Suharsono 1990; Glynn 1991; Gleason 1993; Glynn 1993; Brown *et al.* 1995; Phongsuwan 1995; Spencer *et al.* 1998; Fabricius 1999; Riegl 1999; Marshall and Baird 2000; McClanahan 2000; Westmacott *et al.* 2000; Edwards *et al.* 2001; Lindahl *et al.* 2001; Wellington *et al.* 2001). The widespread bleaching events that have repeatedly occurred since the early 1980s have resulted in dramatic changes in reef environments, some apparent coral extinctions (de Weerdt and Glynn 1991; Glynn 1991; Glynn and Feingold 1992; Glynn 2000; Fenner 2001), and concern that corals and coral reefs are in danger of serious decline over the next century as a major tropical marine biotope (Hoegh-Guldberg 1999).

The major influence causing coral bleaching is increased ocean temperature, especially during periods of El Niño Southern Oscillation (ENSO) (Williams and Bunkley-Williams 1988; Glynn 1989; Brown and Suharsono 1990; Glynn and D'Croz 1990; Williams and Bunkley-Williams 1990; Glynn 1991; Glynn 1993; Spencer *et al.* 1998; Wilkinson *et al.* 1998; Glynn 2000; Wellington *et al.* 2001) although major bleaching events have occurred outside of ENSO periods (Brown 1987). It is apparent that the major causes of bleaching events are unpredictable and uncontrollable, and probably are linked to climatic conditions that may become more stressful over at least the next century (Wellington *et al.* 2001). Given that we are dealing with a worldwide phenomenon, is it possible to optimize conditions that will maintain reservoirs of stress tolerant corals to survive bleaching events and promote increased recovery of reef corals between bleaching events? The concept of mitigating impacts of coral bleaching through establishment of new or modification of existing Marine Protected Areas (MPAs) has been proposed (Westmacott *et al.* 2000; Salm *et al.* 2001) as a means to promote coral survival and recovery, and is the subject of the present workshop. To provide a biological context for the causes of coral bleaching and introduce the topics that will be presented and discussed by workshop participants, the following short review is presented.

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What Do We Know About Coral Bleaching?

Atmospheric and Ocean Temperature Changes

The earth's atmosphere and oceans have warmed significantly in the last century, resulting in an estimated average increase in ocean temperature of 0.5°C (Pittock 1999). Even higher temperatures ranging up to 3°C over normal ambient maxima for substantial periods have occurred frequently in the last 30 years, often but not exclusively during ENSO periods, and these periods of elevated temperature have been quickly followed by major coral bleaching events. Such major coral bleaching events corresponding to ENSO periods have occurred 6 times in the last 20 years (Wellington *et al.* 2001), with the worst episode in 1997-1998 affecting large areas throughout the Indo-Pacific and Caribbean (Cohen *et al.* 1997; Baird and Marshall 1998; Spencer *et al.* 1998; Wilkinson *et al.* 1998; Berkelmans and Oliver 1999; Berkelmans and Willis 1999; Fabricius 1999; Hoegh-Guldberg 1999; Mumby 1999; Marshall and Baird 2000; McClanahan 2000; Westmacott *et al.* 2000; Edwards *et al.* 2001; Lindahl *et al.* 2001; Wellington *et al.* 2001).

Coral Temperature Thresholds

Research conducted on coral temperature tolerances during the early 1970s (Coles 1973; Jokiel and Coles 1974; Coles *et al.* 1976; Jokiel and Coles 1977; Coles and Jokiel 1978; Jokiel and Guinther 1978) verified early observations (Mayer 1914) that reef corals are highly sensitive to temperature increases and concluded that "in both subtropical and tropical environments large populations of corals are exposed to temperatures precariously close (within 1-2°C) to their upper lethal limit during the summer months" (Coles *et al.* 1976). The literature is now replete with reports and experimental results indicating that this small temperature tolerance threshold exists for corals worldwide, and that coral bleaching is predictable whenever temperatures exceed long term annual maxima by 1-3°C for periods longer than about a week (Hudson 1981; Lasker *et al.* 1984; Harriott 1985; Oliver 1985; Gleason 1993; Glynn 1993; Phongsuwan 1995; Spencer *et al.* 1998; Berkelmans and Oliver 1999; Fabricius 1999; Hoegh-Guldberg 1999; Marshall and Baird 2000; Westmacott *et al.* 2000; Edwards *et al.* 2001; Lindahl *et al.* 2001; Michalek-Wagner and Willis 2001; Wellington *et al.* 2001). These thresholds are clearly linked to ambient temperature environments with mass bleaching having been triggered by temperatures as high as 35°C in the Arabian Gulf where normal ambient maxima is 33-34°C (George and John 1998; Riegl 1999), to as low as 27°C at Rapa Nui (Easter Island) where average normal maximum temperatures is 25°C (Hubbard and Garcia 2000; Wellington *et al.* 2001). Also, the duration of the exposure is critical in determining the extent and impact of coral bleaching, with likelihood of recovery from short term exposures much greater than for exposures of a week or more (Coles *et al.* 1976; Jokiel and Coles 1977; Coles and Jokiel 1978; Fitt and Warner 1995).

Biological Model of Coral Bleaching

During coral bleaching events not all corals are equally affected and even adjacent corals of the same species can show different levels of bleaching ranging from highly bleached to apparently unaffected (Lasker *et al.* 1984; Brown *et al.* 2000; Marshall and Baird 2000), indicating that coral bleaching is not a simple direct response to increased temperature. Also, individual corals usually show more pronounced bleaching and mortality on upper surfaces and on terminal branches than lower on the colony. These observations substantiate earlier experimental findings (Coles 1973; Jokiel and Coles 1977; Coles and Jokiel 1978) that high levels of light interact with increased temperature in producing coral bleaching. More recent research has clarified the relationship between light and temperature as sources of stress to zooxanthellae symbionts, which results in their separation from the coral host (Iglesias-Prieto *et al.* 1992; Fitt and Warner 1995; Warner *et al.* 1996; Brown 1997b; Jones *et al.* 1998; Hoegh-Guldberg 1999; Warner *et al.* 1999; Brown *et al.* 2000; Jones *et al.* 2000; Fitt *et al.* 2001). In brief, elevated temperatures increase rates of the hydrogen ion production in the light reactions of photosynthesis, producing more protons than can be utilized to form organic carbon in the dark reaction. Instead, these hydrogen ions are passed to oxygen to form superoxides or oxygen free radicals (Lesser *et al.* 1990). If these oxygen compounds are not rendered nontoxic by enzymes they further reduce photosynthetic processes (Lesser 1997) and ultimately result in algal chloroplast disruption (Salih *et al.*1998) and zooxanthellae loss, i.e., bleaching.

Internal Protections from Coral Bleaching

Photoinhibition under the influence of increased temperature is therefore a primary factor influencing coral bleaching, and both internal and external processes that effectively reduce light levels or alter light quality to longer, less toxic wavelengths have potential in reducing coral bleaching when increased temperatures occur. Recent studies have shown the importance of fluorescent coral pigments in reducing coral bleaching by reflecting and/or fluorescing absorbed light (Salih *et al.*1998; Salih *et al.* 2000; Dove *et al.* 2001). Corals containing such fluorescent capacity were found to bleach significantly less than non-fluorescent colonies of the same species (Salih *et al.* 2000). Other internal protection mechanisms that may influence resistance to coral bleaching and mortality are the presence of micosporine-like amino acids (Kuffner 2001), and induced changes in heat shock proteins (Brown 1997a; Gates and Edmunds 1999).

Long-term Impacts

Unless coral bleaching is very prolonged, there are usually varying levels of recovery of some affected corals, with restoring of zooxanthellae within coral tissues and continued skeletal growth. However, chronic changes from coral bleaching have been demonstrated or indicated which are likely to affect the long-term viability of corals on reefs. Of primary concern is the impact of bleaching on coral reproduction and settlement. Experiments on both a hard coral in Florida and a soft coral on the Great Barrier Reef have shown reduced fecundity for bleached corals that resulted in delay in spawning of one year (Michalek-Wagner and Willis 2001) or inability to complete gametogenesis (Szmant and Gassman 1990). Experiments in Hawaii found coral settlement to be highly sensitive to temperature increases (Jokiel and Guinther 1978), with 10-fold reductions at an increase of 1°C above the annual temperature maximum. Reduced fecundity is indicated to result from lower energy resources available to a coral that has survived and recovered from a bleaching episode (Szmant and Gassman 1990). Lower energy reserves due to prolonged and repeated coral bleaching are also the likely cause of the extensive outbreaks of coral diseases that have occurred in Florida and Caribbean waters in the last decade (Causey, this volume).

What Do We Think We Know About Coral Bleaching?

Ocean Environment

Ocean Temperature. Various mathematical models predict global warming over the next century that will resulting in a rise in ocean temperature of 1-3°C (Boesch *et al.* 2000). However these projections are not without their critics and an alternate viewpoint is that the "greenhouse effect" of increased atmospheric CO2 and other gases will result in global cooling. Therefore, projections of coral bleaching in response to continued warming of the earth's oceans must be viewed within this uncertain context, although the global warming scenario appears to be becoming more rigorous and accepted as models are refined (Barnett *et al.* 2001; Levitus *et al.* 2001).

Carbon Dioxide Content. Atmospheric CO2 concentrations have risen exponentially in the last century and a half, and extrapolation of this increase indicates a doubling of atmospheric CO2 above pre-industrial era levels by about 2060, even if the Kyoto Protocol for carbon emission controls are implemented worldwide (Pittock 1999). This represents a potential decrease in ocean pH and total alkalinity that experimental simulations indicate will significantly reduce coral calcification independent of temperature effects (Gattuso *et al.* 1999).

Continued Unpredictable ENSO Events. Regardless of baseline levels of ocean temperature increase, ENSO events will continue at a probable frequency of at least every five years, and these periods are very likely to produce widespread coral bleaching. However, the amplitude of the ENSO events and the levels or time periods of corresponding temperature elevations are not predictable.

Coral Impacts

Continued Coral Bleaching. Repeated coral bleaching episodes are anticipated worldwide at an unknown frequency for the next century. In addition to these periodic bleaching events, various climate models have been interpreted to indicate that presently indicated coral bleaching thermal thresholds for different geographic areas will be exceeded on an annual basis by 2030 due to a steadily increasing ocean baseline temperature (Hoegh-Guldberg 1999). Although projections of the rate of increase in ocean temperature are subject to criticism and refinement, it seems reasonable to anticipate that temperatures above presently accepted bleaching thresholds will occur frequently through the next century, and that these events will continue to result in widespread coral mortality unless coral-algal adaptive mechanisms take place.

What Don't We Know About Coral Bleaching?

Effect and Extent of Coral Adaptation

Countering the conclusion that widespread coral bleaching will lead to inevitable reef decline is the possibility that corals may adapt sufficiently rapidly to an increasing and erratic temperature environment. Available information is insufficient to determine whether such a rapid adjustment of coral-algal temperature thresholds can occur. However, experimental results and observations provide some information indicating that such adaptation is possible, which may help to ameliorate the worst impacts of ocean warming and coral bleaching.

Acclimation. Short-term acclimation to elevated temperature has been shown in a single experiment for the Hawaiian coral Montipora verrucosa (Coles and Jokiel 1978). Bleached colonies exposed to temperatures to 2-5°C above summer ambient for 56 days had higher survival rates (74%) to one exposure at 32.5 °C than did corals previously held at 26°C (61%), 24°C (30%) or 26°C (40%). Experiments by Clausen and Roth (1975), showed shifts in coral calcification rates of Hawaiian *Pocillopora damicornis* corresponding to incubation temperature, suggesting a capacity for sublethal short-term acclimation. Al-Sofyani and Davies (1992) found that respiration rates of *Echinopora gemmacea* in the Red Sea did not change with a 6°C seasonal change in seawater temperature, suggesting acclimation for this species, while respiration rates of *Stylophora pistillata* indicated no such acclimation.. On the Great Barrier Reef (Berkelmans and Willis 1999) found that the winter bleaching threshold of *Pocillopora damicornis* on the Great Barrier reef was 1°C lower than its summer threshold, which they interpreted to indicate that seasonal acclimatization may take place for this species. No other information is available concerning acute temperature acclimation capability for corals, indicating a need for further research in this area.

Acclimatization In contrast to the limited information available concerning coral-algal acclimation, substantially more is known concerning responses in the composition of zooxanthellae symbionts that would enable medium term acclimatization. According the Adaptive Bleaching Hypothesis (ABH) posed by Buddemeier and Fautin (1993), the loss of resident zooxanthellae in response to stress provides an opportunity for stress-adapted types to repopulate the coral, imparting greater resistance to the stress and competitive advantage for the coral-algal complex. Considerable evidence from recent studies supports the ABH for corals, as well as other cnidarians, which have symbiotic algae subject to bleaching (Baker 2000, 2001; Coffroth 2000; Jacobs 2000; Kinzie *et al.* 2001). These results indicate that a high genetic diversity and capacity for phenotypic adaptation of the zooxanthellae symbionts that may act to promote acclimatization of the coral algal complex to increased temperatures (Brown 1997a; Brown 1997b).

Selection No direct measurements of long term selection for temperature tolerance in corals exposed to specific bleaching events have been made, and evidence for temperature tolerance selection both within and among coral species is circumstantial. The primary evidence of long term selection for temperature tolerant corals is based upon linkages of thermal thresholds to maximum ambient temperature environments and reports of corals surviving temperatures well in excess of normally considered limits. Gardiner (1903) observed abundant corals in a tidepool in the Laccadives at 56°C and Kinsman (1964) noted massive *Porites* at over 40°C near Abu Dhabi, Arabian Gulf . Vaughan (1914); Orr and Moorhouse (1933) and Motoda (1940) reported corals surviving up to temperatures of 38-39°C in Florida, Australia, and Palau, respectively. More recently Tomascik *et al.* (1997) described a variety of corals living at 34-37°C near a thermal vent in Indonesia, with one species growing in the vent at 42°C. These extreme examples demonstrate a large capacity for adaptation and selection by at least a few coral species. However, nothing is known about the conditions or timeframe under which this capacity was acquired, and the relevance of these examples for widespread adaptation to coral bleaching is uncertain.

Combined Effects of Dissolved CO_2 and Temperature

The increased ocean acidity that is likely to result from increased atmospheric concentrations of CO_2 will, on its own, cause reduction in coral calcification. As shown by (Gattuso *et al.* 1999) a doubling of actual CO_2 concentrations in the atmosphere could lead to decreases in calcification rates of 9-30%. We do not know how such reduction in coral calcification and growth will interact with the impacts of coral bleaching. However, it is known that temperature increases above temperature optima result in decreases in coral calcification (Clausen and Roth 1975; Jokiel and Coles 1977; Coles and Jokiel 1978; Jokiel and Coles 1990), which would result in further decreasing calcification rates already reduced by lower ocean pH.

Bleaching Impact on Other Major Reef Components

Assuming a worst case scenario of annual coral bleaching and widespread reductions in diversity and abundance of reef corals occurring worldwide in 30 years, it is unclear how this might impact other major components of the coral reef system. Certainly those fishes and macroinvertebrates that are symbionts of living corals would be equally diminished, but for the majority of reef organisms not directly linked to corals, the total result of pervasive coral bleaching is impossible to predict. Various scenarios have been presented by Done (1999) which include coral tolerance and adaptation, shifting of coral populations to smaller size classes, changing of species compositions toward more tolerant coral species with probable decreases in diversity, and phase shifts to reefs dominated by fleshy macroalgae instead of corals and coralline algae. Although all of these alternatives are likely to result in less attractive reefs, we do not know that the reefs would be functionally diminished as biotic systems. Species diversity and abundance of invertebrates would possibly increase in the short term as new habitat spaces were opened up in recently dead corals (Coles 1980). Regarding fish assemblages Lindahl *et al.* (2001) found that fish community diversity was unchanged after the 1998 bleaching event that killed 88% of corals on Tanzanian reef plots, but fish abundance rose 39%, mostly due to increase in herbivores apparently responding to a greater availability of macroalgae.

This limited information suggests that although undesirable in human terms, the initial ecological impacts of widespread coral bleaching and mortality may not be ecologically devastating. However, over the longer-term, coral bleaching is likely to reduce rates of coral reproduction, recruitment, disease, reduced reef calcification and associated degradation of reef habitat, and impacts on human populations through reduced wave protection, lost reef aesthetics, and diminished revenue potential. These implications of worldwide and repeated coral bleaching warrant major concern and an evaluation of actions that might help to mitigate the impacts of bleaching and promote reef recovery.

What Can We Do?

It may be that the extent, frequency, and amplitude of future coral bleaching events will be so pervasive that attempts at countering long-term impacts will be ineffective. However, such a defeatist attitude can only assure a negative result, and it is contingent on coral scientists and reef managers to examine ways to deal with this problem. One approach that might be proposed would be to embark on a program of transplanting corals with known high temperature tolerances from areas such as the Red Sea or Arabian Gulf to act as seeding agents on reefs that have undergone extensive bleaching. This would not be a valid approach ecologically or economically, and would have its own predictable and unpredictable dangers. Such a program would be have to be exceedingly large and expensive if it were to make any impact, could only involve the relatively few species that occur in the source areas, and would be likely to be ineffective due to limited survival of transplants subjected to handling and disturbance. Moreover, nonindigenous organisms and/or parasites that came with the transplanted corals could have negative to devastating impacts of their own in the reef systems where they were introduced.

A more realistic approach to mitigating the impacts of coral bleaching would be to implement a system of MPAs that would include reefs that would have corals with a higher likelihood of surviving bleaching events and act as sources of replenishment for reefs highly impacted by bleaching. The general characteristics of such MPAs have been described by Salm *et al.* (2001) and Westmacott *et al.* (2000) and the specifics for their location and implementation are the subject of this workshop. Subjects to be considered include the environmental factors which both promote the survival of corals during times of bleaching-related stress and how these areas might promote recolonization and recovery of highly impacted reefs (West, this volume), and what scientific principals may apply for MPA establishment (Done, this volume). An important aspect of this program will be to decide on appropriate methods of monitoring the effectiveness of MPAs in coral bleaching mitigation, and descriptions of and lessons learned from coral reef monitoring programs in place in Hawaii (Jokiel, this volume), the Indian Ocean (Obura, this volume) and Great Barrier Reef (Oliver, this volume) are presented. Historical aspects of coral bleaching events that have occurred over the past 20 years in the East Pacific (Glynn, this volume) and the Florida Keys (Causey, this volume) are presented, and indirect impacts on corals and reefs, such as incidences of coral disease following bleaching events, are described.

The perception appears to be growing in the popular media and perhaps even among some coral reef scientists that coral bleaching will lead to inevitable degradation and demise of coral reefs as a major tropical biotope within the next 50 years. Although the information is not encouraging in terms of the environmental stresses that are likely to occur, there are also indications that reef corals have "potential for greater physiological tolerance than might have been previously expected" (Done 1999) and that "bleaching susceptibility due to external environmental factors can be studied and incorporated in management planning" (Salm *et al.* 2001). A system of MPAs, established using the best available scientific information related to environmental factors favoring coral survival and propagation, offers the most promising approach to mitigating the impacts of worldwide coral bleaching.

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History Of Significant Coral Bleaching Events And Insights Regarding Amelioration

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Introduction

The first documented mass bleaching of reef-building corals was correlated with natural elevated sea temperatures that occurred in the eastern Pacific during the very strong 1982-83 El Niño-Southern Oscillation event (Glynn 1984; Robinson 1985). This disturbance event resulted in significant to catastrophic coral mortalities on all surveyed reefs over the entire eastern equatorial Pacific region. Other smaller scale coral bleaching events were reported during the first half of the 20th Century, but they were localized and resulted from extreme low tidal exposures, freshwater dilution, experimentally altered conditions or unknown stressors (Glynn 1993, 1996). Mass coral bleaching events have since occurred throughout the 1980s, 1990s, and are still ongoing (e.g., Easter Island, March 2000, Wellington *et al.*, 2001; Fiji, March-April 2001, NOAA - Coral Reef Watch, 2001). Elevated seawater temperature is usually the major factor causing these bleaching events, often exacerbated by high solar insolation (UVR and PAR wavelengths). As of this writing, all major coral reef regions have been affected, including areas in the eastern, central and western Pacific, Indian Ocean, and western Atlantic. I am not aware of any reports from west Africa, although reef-building coral assemblages do occur in that region. Within the major coral reef regions, bleaching has occurred in relatively cool subtropical areas (e.g., Galápagos Islands, Easter Island, Bermuda) and in areas subject to intense summer heating (e.g., Persian Gulf and Gulf of Oman).

Beginning with the experimental studies of Jokiel and Coles in the 1970s (see Jokiel and Coles 1990), it became readily apparent that reef corals lived perilously close to their upper thermal tolerance limits. These studies, and the El Niño simulation experiment conducted by Glynn and D'Croz (1990), provided further evidence that prolonged elevated water temperature was the master factor responsible for coral bleaching. For further information on coral bleaching and global temperature rise, the reader is referred to Williams and Bunkley-Williams (1990), Goreau *et al.* (1993), Goreau and Hayes (1994) and Hoegh-Guldberg (1999). Additional studies have demonstrated that natural high irradiance alone, or more commonly in combination with high water temperature, can also induce bleaching (Brown, 1997a). Taking the lead from Jokiel (1980), much recent attention has focused on the deleterious effects of UVR, especially UVB radiation (Gleason and Wellington 1993; Gulko and Jokiel 1995; Shick *et al.* 1996). The types of endosymbiotic zooxanthellae present, which exhibit varying degrees of susceptibility to irradiance and thermal stressors, largely determine intra- and intercolony patterns of bleaching (Rowan *et al.* 1997).

Since information on the history of coral bleaching events, causative factors, and the responses of coral hosts and algal symbionts is available in the referenced literature above, I choose to concentrate here on two topics that have received less attention, but are relevant to this workshop, namely (1) the types of environments displaying minimal bleaching, and (2) the nature of reef habitats exhibiting the greatest recovery potential following bleaching/mortality events. Most of the following discussion will relate to examples from the eastern tropical Pacific region. It is hoped that this brief survey will stimulate comparisons with other regions.

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Minimally-Disturbed Habitats

Upwelling areas. Two upwelling centers in the eastern Pacific suffered relatively low rates of coral bleaching and mortality compared with non-upwelling environments during the 1997-98 ENSO event. In spite of a general ENSO sea warming trend off coastal Panamá, seasonal upwelling in the Gulf of Panamá occurred on schedule and SSTs never reached threshold bleaching levels (Glynn *et al.*, in review). Gulf of Panamá mean SSTs during the 1997-98 ENSO were 27°C with maximum values of 29°C. Mean 1997-98 ENSO SSTs in the non-upwelling Gulf of Chiriquí were 30°C with 30.5-31.0oC SSTs that lasted for several weeks and were coincident with high level coral bleaching and mortality. A similar depression of SSTs in the Papagayo upwelling center of Costa Rica was observed in 1997-98 with relatively low level coral bleaching and mortality (Jiménez *et al.*, in press). Even though corals in these upwelling areas were not exposed to elevated temperatures in 1997-98, this was not the case in the Gulf of Panamá in 1982-83. At that time, upwelling did not occur, SSTs reached nearly 30°C, and corals bleached and suffered about 85% overall mortality (Glynn *et al.*1988).

Deep areas. Although deep reef-coral habitats contain different species assemblages than shallow habitats, lower incidences of bleaching and mortality were observed in the former in the eastern Pacific during both the 1982-83 and 1997-98 ENSO warming events. Fungiids *(Cycloseris, Diaseris)* and *Psammocora* spp. in particular, and occasional, normally shallow-living species (e.g., *Pocillopora* spp., *Porites lobata*, *Pavona* spp.), demonstrated high rates of survival in the Galápagos Islands and off Panamá. *Millepora intricata,* a hydrocoral, survived at 15 m depth in the Gulf of Chiriquí, Panamá in 1997-98. And deep surviving *M. intricata* colonies were probably the source of reproductive propagules that allowed the recovery of this species following the 1982-83 event. At that time, all *M. intricata* in shallow habitats (5 m) had bleached and died. This higher survivorship below the reef base is probably due to lower temperature conditions and reduced light penetration below 10-12 m.

Habitats with rapid current flow. The possibility that habitats subject to strong currents suffer lower rates of coral bleaching has not been systematically studied. Observations in Panamá during natural bleaching events suggest that coral populations inhabiting rocky points and coastal prominences that are swept by strong currents are generally less affected than areas with sluggish currents. Espejo Point at Marchena Island is swept by strong currents, and supports perhaps the most diverse and luxuriant coral communities in all of the Galápagos Islands, despite the 1982-83 and 1997-98 ENSO disturbances. More study is needed, however, to evaluate the relative importance of high coral survivorship during sea warming versus high recruitment following bleaching events in these habitats.

Onshore-offshore gradients. Coral mortality resulting from the 1997-98 ENSO bleaching event in the eastern Pacific demonstrated a trend of increasing intensity from nearshore to offshore or oceanic sites (Glynn *et al.*, in review). This pattern was observed in the Gulf of Chiriquí (Panamá) and in Ecuador. For example, in Panamá, overall coral mortality was significantly higher at Montuosa (55%) and Jicarón (12%) islands than at Uva (3%) and Silva (4%) islands, which are located relatively close to the mainland. In Ecuador, all 10 Galápagos sites revealed over 10% coral mortality each, whereas four of five mainland sites experienced less than 7% mortality. Los Frailes, an exceptional mainland site, experienced 76% mortality. This high value is based on only 34 colonies of *Pocillopora damicornis*, a particularly vulnerable species to high temperature stress. This offshore-to-inshore decline in mortality is possibly a result of higher stressful SSTs that are prevalent in more oceanic settings during ENSO activity. Additionally, water clarity would be higher offshore, thus allowing for greater light penetration and irradiance stress. These eastern Pacific observations are supported by a similar bleaching gradient in Bermuda in 1988 (Cook *et al.* 1990), but not at reef sites on the Great Barrier Reef in 1998, which demonstrated the opposite trend (Berkelmans and Oliver 1999). Nearshore reefs in Australia suffered the highest rates of bleaching and mortality, likely a result of the interactive effects of low salinity and high sedimentation that accompanied the period of elevated temperatures.

Areas Exhibiting The Greatest Recovery

To a large extent, recovery rates will depend upon the complement of coral species remaining in an area following a bleaching disturbance. Some species are more resistant to bleaching than others (Brown 1997b), and some species demonstrate rapid tissue recovery or are able to quickly repopulate affected areas by sexual and asexual propagation (Pearson 1981).

Upwelling. Permanent plots on reefs in Panamá allow a comparison of coral recovery in upwelling (Saboga Island) and non-upwelling (Uva and Secas Islands) habitats following the 1982-83 ENSO bleaching event. Both upwelling and non-upwelling pocilloporid reef slopes exhibited between 50 to 60% live cover in 1982. Live coral cover in the study plots was reduced to 0% following the ENSO disturbance in 1983. By 1992, study plots in the upwelling environment had recovered to their pre-disturbance levels, and continue to support high pocilloporid cover (as of March 2001). By 1997, plots at non-upwelling sites supported only 3 to 6% live cover. Some amount of this cover, not yet calculated, was further reduced by anomalous sea warming and bleaching during the 1997-98 ENSO.

Deep areas. A relatively deep (13-15 m) *Diaseris/Psammocora* community in the Galápagos Islands experienced extensive bleaching during both recent (1982-83, 1997-98), very strong ENSO events. Mortality, however, was virtually undetectable and recovery, i.e. the total area of live, normally pigmented coral cover, was complete (matching 1975 and 1976 levels) within a few months following the disturbance (Feingold, in review). In Panamá, the hydrocoral *Millepora boschmai* disappeared from shallow reef habitats during the 1982-83 ENSO, and was believed to have suffered extinction (Glynn and de Weerdt 1991). A survey in a relatively deep, off-reef habitat about nine years following the first disappearance of *M. boschmai* revealed a living population of under 100 colonies (Glynn and Feingold 1992). Evidently this population, located on the north shore of Uva Island (named Lazarus Cove), Gulf of Chiriquí, Panamá, survived the 1982-83 ENSO warming event. Unfortunately, all of these colonies bleached and died six years later, during the 1997-98 ENSO.

Another critically endangered scleractinian species *(Siderastrea glynni)* that began to bleach in 1998 was moved from its natural habitat to aquaria at Naos Island (Smithsonian Tropical Research Institute), Panamá, where it is being cared for by Héctor Guzmán (Fenner 2001). Since only 5 colonies of this species were known, and one colony recently died in the field, Guzmán's attempt at coral husbandry seems justified.

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Environmental Determinants Of Resistance To Coral Bleaching: Implications For Management Of Marine Protected Areas

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Abstract

The massive scale of the 1997-98 El Niño-associated coral bleaching event underscores an urgent need for rapid action to mitigate temperature-induced coral mortality and consequent biodiversity losses due to rising baseline sea surface temperatures. One approach, proposed by Salm *et al.* (2001), would be to identify and strictly protect from direct anthropogenic impacts specific reef communities or areas where natural environmental conditions are likely to result in low or negligible temperature-related bleaching and mortality. These "pockets of resistance", where environmental conditions appear to boost coral survivorship during and after large-scale bleaching events, could then be incorporated into strategic regional networks of marine protected areas (MPAs) designed to maximize overall conservation of global coral reef biodiversity. This paper addresses the first step of this process, which is the identification of environmental determinants of resistance to coral bleaching. This includes an assessment of: environmental factors that may account for differential susceptibility of corals to bleaching, mortality, and recovery; suggestions for testing the significance of the identified factors through targeted monitoring; and some implications of this approach for evaluation and design of MPAs.

Introduction

Coral reefs are one of the most threatened global ecosystems, and also one of the most vital. Reefs are of critical importance to human survival (especially in developing countries) as they provide subsistence food for a substantial portion of the population, serve as the principle coastal protection structures for most tropical islands, and contribute major income and foreign exchange earnings from tourism (Westmacott *et al.* 2000; Salm *et al.* 2001). In addition, coral reefs provide habitat for some of the highest biological diversity in the world (Ray 1988).

Reef-building (Scleractinian) corals form complex structures that serve as the foundation for highly diverse coral reef communities. For growth of these structures, the corals are highly dependent on their symbiotic single-celled algae (zooxanthellae), which provide up to 95% of the corals' carbon requirements (Muscatine 1990) as well as most of their color. The combination of photosynthesis and physiological processes of the coral produces the calcium carbonate coral skeleton. Gradual accretion of coral skeletons results in massive three-dimensional frameworks, which provide habitat for reef communities that exceed terrestrial rainforests in their diversity (Ray 1988).

Unfortunately, reef-building corals and their zooxanthellae are vulnerable to a variety of environmental stressors that can disrupt the symbiotic relationship and cause "bleaching". These stressors include freshwater flooding (Goreau 1964; Egana and DiSalvo 1982), pollution (Jones 1997; Jones and Steven 1997), sedimentation (Meehan and Ostrander 1997), disease (Kushmaro *et al.* 1997; Benin *et al.* 2000), increased or decreased light (Lesser *et al.* 1990; Gleason and Wellington 1993), and especially elevated or decreased

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sea surface temperatures (SSTs) (Glynn 1993; Brown 1997; Hoegh-Guldberg 1999). Bleaching occurs when, alone or in combination, environmental stressors cause the degeneration and expulsion of zooxanthellae from the coral host, such that the white skeleton becomes visible through the transparent coral tissue. During a bleaching event, corals may lose 60-90% of their zooxanthellae, and the remaining zooxanthellae may lose 50-80% of their photosynthetic pigments (Glynn 1996).

Once the stress subsides, corals can often recover and regain their previous levels of zooxanthellae; however, this depends on the intensity and duration of the stress (Hoegh-Guldberg 1999). Prolonged exposure can result in partial or complete death of not only individual coral colonies, but also large tracts of reef. Bleached corals, whether they die totally or partially, are more vulnerable to algal overgrowth, disease, and reef organisms that bore into the skeleton and degrade the reef structure (Westmacott et al. 2000). As reefs disintegrate, patterns of coral species diversity can be altered dramatically, and the reef community may be restructured (Done 1992; Hughes 1994), with consequent impacts on the diversity of fish and other organisms within the reef ecosystem.

Depending on the type and extent of the stressor(s), coral bleaching can be patchy and localized, or widespread over large geographic scales. Salm *et al.* (2001) point out that small-scale, localized bleaching events are often due to direct anthropogenic stressors (e.g., pollution or freshwater runoff), which can be prevented through abatement of the stress at its source. In these cases, poor management practices in adjacent riparian zones can be corrected (e.g., reforestation and other erosion and flood control measures) in order to minimize the threat at its origin. Such interventions should form part of any integrated coastal management or MPA management program (Salm *et al.* 2000).

Unlike the localized bleaching events described above, large-scale bleaching events can not be fully explained by localized stress factors and instead have been strongly linked to the presence of increased sea surface temperatures (SSTs) at regional scales (Wilkinson 1998, 2000; Salm *et al.* 2001). These large-scale events have increased in frequency and severity over the last two decades, and in 1997-98, the distribution of HotSpots[2] and subsequent bleaching coincided with the largest El Niño-Southern Oscillation (ENSO) on record. Bleaching spanned the tropics in over 50 countries, reflecting the global nature of the event (Wilkinson 1998, 2000), with near complete loss of live coral in some regions (Goreau *et al.*. 2000). If average temperatures continue to increase due to global climate change, then corals will likely suffer even more frequent and severe bleaching events in the future. Thus, climate change may now be the single greatest threat to reefs worldwide.

From a manager's perspective, large-scale SST changes linked to global warming and ENSO events can not be readily addressed at the source to control the stress -- at least not in meaningful time frames given the increasing frequency and severity of these events. In a paper presented at the 9th International Coral Reef Symposium (2000) in Bali, Indonesia, Salm *et al.* (2001) noted this problem and proposed that through thoughtful planning and strategic care of reefs within existing and future marine protected areas (MPAs), it may be possible to take advantage of natural properties of coral reef ecosystems to mitigate the impact of bleaching and related mortality in two broad ways:

[2]A HotSpot is an area where sea surface temperatures (SSTs) have exceeded the expected yearly maximum (a ten year average of the highest mean monthly temperature per year) for that location (Goreau and Hayes 1994)

1. Recognize and strictly protect from direct anthropogenic impacts specific reef communities or areas where environmental conditions are more likely to result in low or negligible temperature-related bleaching and mortality (i.e., a high level of resistance), and;

2. Enhance coral reef recovery (resilience) by ensuring that conditions are optimal for larval dispersal and recruitment to damaged sites. This will require minimizing other stresses at these sites (abatement of direct localized impacts) and understanding larval dispersal (connectivity) to encourage recolonization.

As stated by Salm *et al.* (2001), the goal is to develop a robust set of principles to mitigate bleaching-related mortality and help managers to identify, design and manage networks of MPAs that will maximize overall survival of the world's coral reefs in the face of global climate change. The most useful approach will be one that utilizes natural processes rather than expensive technological fixes and helps managers to focus management and enforcement efforts to most critical areas. Given the limited capacity and funding available for management in many coral reef countries, what is especially needed are simple tractable strategies that any manager can adopt immediately to maximize the probability of long-term survival for the broadest range of coral communities and reef types possible.

This paper further develops these ideas and builds upon the work of Salm *et al.* (2001) by addressing the first step of this process: identifying environmental determinants of resistance to coral bleaching and their implications for MPA management. Patterns of coral bleaching and related mortality evident after the 1997-98 ENSO provide some insights into where to begin.

Environmental Determinants of Resistance to Coral Bleaching: The Evidence

During coral bleaching events, there is never total elimination of all corals on an entire reef; even in the severest cases, scattered colonies and patches of reef survive (i.e., show resistance). One goal, then, could be to identify the determinants of these "pockets of resistance", where environmental conditions appear to boost coral survivability during large-scale bleaching events.

For the purposes of this paper, the term *resistance* refers to the ability of individual corals to resist bleaching, or to successfully recover after they have been bleached. Such resistance may be due to either or both of the following: 1) intrinsic, species-specific physiological tolerance; and 2) extrinsic environmental factors that afford some (but not necessarily full) protection from bleaching conditions, such that a subset of corals have a higher probability of surviving bleaching events. In the case of condition (1), *resistance* corresponds with Done's (1999) use of physiological "tolerance" to describe persistence in the face of disturbance such that there is no change in longevity of individual corals (although sub-lethal bleaching may occur). Condition (2) extends the definition of *resistance* to include situations where localized environmental factors serve to boost resistance of a local coral assemblage, whether or not the individual corals have any intrinsic physiological tolerance. In this case, resistance refers to environmentally provided (extrinsic) "tolerance" in the form of partial protection from bleaching conditions.

High sea surface temperatures (SSTs) and solar radiation are major stressors that interact to cause severe coral bleaching and mortality, and are responsible (either alone or in combination) for the majority of global-scale coral reef disturbances (see multiple references in Glynn 2000). Therefore, resistance to coral bleaching may be enhanced by any environmental factor that reduces temperature, blocks irradiance levels reaching corals, or both. Furthermore, since one of the results of bleaching is the production of toxic free radicals (Nakamura and van Woesik 2001), corals that are flushed by high volumes of water may also be at an advantage (see below). Finally, there may be environmental characteristics that favor pre-adaptation (physiological tolerance) of corals to resist coral bleaching – such as the presence of regularly stressful environmental conditions. Based on this information and on numerous observations from the 1997-98 ENSO and other bleaching events of the past, we can break down the environmental determinants of resistance to bleaching into four broad categories.

Enhanced Water Movement that Flushes Harmful Bleaching Toxins

In some cases, meso-scale oceanographic processes can counteract sea warming at local scales: for example, the "island mass effect" can cause turbulence and vertical mixing on the leeward sides of islands subject to strong current flow (Glynn 1993). This process can lead to some cooling through vertical mixing and upwelling of deeper cooler waters (see also upwelling section below). Yet, even at uniformly high temperatures, increased flow rates alone may confer some protection from bleaching.

Nakamura and van Woesik (2001) empirically tested the notion that – since the photoinhibition phenomenon that accompanies bleaching involves the accumulation of harmful oxygen radicals – high current speeds could actually prevent bleaching by inducing high-mass transfer of detrimental photosynthetic byproducts out of the colony. Under controlled conditions of constant temperature (30°C or greater) and light (30% PAR), *Acropora digitata* colonies under low-flow conditions (< 3 cm/s) suffered high bleaching mortality while colonies under high-flow conditions (50-70 cm/s) showed no bleaching effects (Nakamura and van Woesik 2001). Hence, high water-flow may prevent, through diffusion, excessive build-up of toxins within corals subjected to high SSTs and high irradiance. This can prevent bleaching or minimize mortality after bleaching.

Various field observations appear to support these conclusions. In the southern Seychelles, the channel into Alphonse atoll (where there is fast water flow) was relatively unscathed by the 1997-98 bleaching event, with abundant healthy massive, branching and fire corals unaffected (Clare Bradshaw, pers. obs.). In Indonesia, corals in southern communities where currents are strong – such as Komodo National Park – did not bleach, while those in sheltered northern reefs exhibited bleaching (Pet, pers. obs.). For these examples, however, it must be noted that it is difficult to distinguish between the effect of water movement and the potentially confounding factor of upwelling (see below) in driving these patterns.

Upwelling of Cool Water

Traditionally, areas of cool-water upwelling have been cited as a main cause of poor development of coral reefs. On the other hand, the severity of coral mortality caused by high-temperature ENSO events appears to be far greater than that due to upwelling (Glynn and D'Croz 1990), so upwelling areas can actually protect reefs that would otherwise bleach during regional ENSO events.

In Vietnam, the rapid recovery of reefs from the 1998 bleaching at north Binh Thuan was attributed to the annual upwelling, which brought cold waters to the surface. Reefs elsewhere in Vietnam recovered at a slower rate, implying that reefs near major upwelling areas may suffer less from bleaching events (Chou 2000). Goreau *et al.* (2000) cited observations by local scientists that many central Indonesian reefs were largely spared from severe bleaching in 1997-98, apparently because of upwelling. They also report similar examples of lower bleaching mortality due to upwelling at Alphonse, St. Francois and Bijoutier atolls and certain locations in the Maldives and Western Zanzibar. In an area of local upwelling in the Sultanate of Oman, corals bleached immediately and comprehensively when SSTs reached 39°C, but within days, the temperature had fallen back down to 29°C, and the corals recovered completely over time (Salm 1993; Salm *et al.* 1993).

Unfortunately, oceanic processes and winds that sometimes generate upwelling can also produce alternative conditions that have the opposite effect, worsening the severity of bleaching. For instance, Jokiel and Coles (1990) describe large meso-scale eddies that regularly develop in the lee of Maui and Hawaii during the summer months due to prevailing current and wind patterns. Such gyres can persist for months, stratify, heat 1 to 2oC above the temperature of surrounding waters, and cause coral bleaching. Furthermore, usual patterns of upwelling can sometimes be *disrupted* during ENSO events, when high-pressure systems suppress currents and generate doldrum conditions. Therefore, targeting of upwelling areas as potential sites of survival should be balanced with consideration of whether the upwelling might be disrupted during ENSO events.

This is especially true in light of evidence that corals in upwelling areas may be more sensitive to temperature increases than their counterparts in non-upwelling areas. For example, Glynn and D'Croz (1990) found that experimental high temperatures had a greater negative effect on corals from the Gulf of Panama, which experiences seasonally cool upwellings, compared to corals in the non-upwelling Gulf of Chiriqui. During the 1982-83 ENSO event, warming in the Gulf of Panama was delayed by 3 months compared to the Gulf of Chiriqui -- until after local seasonal upwelling (January-April). The stress response of corals there showed a similar lag, starting in June rather than February; however, while seasonal upwelling protected Gulf of Panama corals initially, these corals were highly vulnerable to the persistent ENSO that extended beyond the protected period, into June. Thus, the timing and persistence of upwelling with respect to ENSOs or other *HotSpot* formations should be a consideration when targeting areas most likely to survive mass bleaching events.

Another source of upwelling (as well as temporary fast currents; see water movement section) is hurricanes. While hurricanes can severely damage coral reefs through physical destruction of reef structures, in some cases they can bring cold deep water to the surface and limit the duration of anomalous temperature exposures to coral reefs in their paths. For example, Goreau *et al.* (2000) noted that previous to 1997-98, bleaching episodes in the Caribbean were most evident in northern sectors such as Jamaica and the Bahamas – in 1998, however, it was the southern sectors that were most severely influenced, possibly due to hurricanes tracking through the northern Caribbean sectors in 1998. McField (pers. obs.) has reported that after the combined impacts of the 1997-98 bleaching event and Hurricane Mitch, overall mortality along Belize's barrier reef was lowest in the central region of the reef. The southern region experienced the heaviest storm impact and consequent physical damage, and also the greatest overall mortality. The northern region suffered little storm damage, yet had the second highest overall mortality due to bleaching. One could speculate that the central region's ranking of lowest overall mortality could have been due to the intermediate degree of impact from the hurricane, such that physical destruction was limited, while fast currents and upwelling brought by the storm minimized bleaching mortality.

Protection from Solar Radiation: Shading, Attenuation, Absorption, Cloud Cover

High solar irradiance, especially in the ultra-violet (UV) spectrum, has a synergistic negative effect with temperature, such that temperature-induced bleaching is exacerbated (Hoegh-Guldberg 1999). Hence, shading of corals, or parts of corals, may moderate the severity of bleaching during ENSO events. Examples include observations of less severe bleaching in fissures (compared to summits of massive corals) and on partially shaded sides of colonies in Costa Rica, Panama (Glynn 1984), the Galapagos Islands (Robinson 1985), and Jamaica (see multiple citations in Glynn and D'Croz 1990). Likewise, Williams and Bunkley-Williams (1990) cite a variety of similar observations, such as Gorgonians bleaching in a striped pattern according to the plane of most direct light, and portions of upper colony surfaces that fell in shadows of fixed objects failing to bleach. In the Rock Islands of Palau, the same species of tabular *Acropora* and *Porites* that were severely bleached and dead in some locations were alive and healthy in appearance in deeply shaded parts of the same reef (Salm, pers. obs.).

Protection from solar radiation can also occur in the form of light attenuation through scattering by suspended particulate matter (turbidity) or by absorption by chromophoric dissolved organic matter (CDOM) in the water column. Goreau *et al.* (2000) reported lower bleaching mortality in very turbid waters in the Gulf of Kutch, Southwestern Sri Lanka, Mahé, and inside the lagoon of Alphonse atoll (Seychelles). In the Florida Keys, CDOM makes a major contribution to the ocean color signal in the short wavelength visible region (Anderson *et al.* in press). Since CDOM absorbs UV radiation much more strongly than visible radiation and generally much more strongly than particulates (phytoplankton and detritus), these recent data indicate that CDOM may control UV penetration in much of the ocean, including coastal habitats for coral assemblages.

Light attenuation from particulate matter and absorption by CDOM can contribute to an inverse relationship between irradiance and depth. Mumby *et al.* (2001) found an inverse depth-mortality relationship for *Porites* in French Polynesia, presumably from exponential attenuation of solar radiation with increasing depth. However, this pattern of protection from bleaching with depth does not always hold true. In some instances, periods of extreme calm, high solar irradiance and clear water can result in equal, or even greater, bleaching mortality of deep-water corals compared to their shallow counterparts, since deep-water corals may have greater sensitivity to UV radiation (Spencer *et al.* 2000).

Finally, cloud cover can also afford protection from solar radiation. In Tahiti, there was no mass bleaching event in 1998, despite severe bleaching elsewhere in French Polynesia. The year 1998 was the cloudiest summer on record, and bleaching did not occur despite high SSTs similar to previous years when bleaching did occur. In a model recently developed by Mumby *et al.* (in press), bleaching was strongly predicted for 1998 based on SSTs and wind speed alone. "No bleaching" was accurately predicted only when cloud cover was included in the model as an additional parameter.

History of Exposure to Stresses

Another category of factors to consider are those that may favor pre-adaptation (physiological tolerance) of corals to resist coral bleaching due to the presence of regularly stressful environmental conditions. For example, the history of exposure to high temperatures can influence the thermal tolerance of corals, and thus their resistance to bleaching (Cook *et al.* 1990; Jokiel and Coles 1990; Marshall and Baird 2000). Coles and Jokiel (1978) concluded that high acclimation temperatures might have increased survival of Hawaiian *Montipora verrucosa* during subsequent thermal stress. This relationship between the temperature history of a reef site and bleaching response is poorly understood, but may be due to a combination of acclimatization of individual colonies and strong selection for tolerant genotypes. For example, small confined areas such as Geoffrey Bay (Great Barrier Reef) may be subject to regular heating events during summer low tides, when water can "pond" over the wide and shallow upper reef (Marshall and Baird, pers. obs.). This type of phenomenon may explain the lower bleaching susceptibility that has been recorded for corals from inner reefs and lagoons relative to conspecifics from deeper waters (Hoeksema 1991). Subsequent observations from the 1997-98 ENSO also support this notion. Reefs with emergent corals that were presumed to be heat-stress tolerant – such as those on the reef flats in the Rock Islands of Palau (Salm, pers. obs.) and Chumbe Island in Tanzania (Riedmiller, pers. obs.) – suffered significantly less bleaching than corals down the reef slopes.

Similar patterns of acclimation or adaptation can be seen along latitudinal and depth gradients. The high-latitude corals of Bermuda are sensitive to elevated temperatures that are within the normal thermal range of corals at lower latitudes, indicating regional differences in temperature tolerance among populations of the same species (Cook *et al.* 1990). Further, some data sets indicate that susceptibility to bleaching and bleaching-induced mortality sometimes increases with increasing depth (Spencer *et al.* 2000), especially during periods of warming that coincide with extremely calm clear waters and high irradiance levels. Lagoonal patch reefs and shallow water corals (3-10 m) may be more tolerant to temperature fluctuations and irradiance than corals in deeper water (10-20 m), which usually experience more constant temperature regimes. This pattern was observed at several locations in the southern Seychelles during the 1997-98 bleaching event (Spencer *et al.* 2000), as well as in Kimbe Bay (Papua New Guinea), where bleaching became increasingly severe below 10 m on platform reefs with mortality highest around 18 m depth (Salm, pers. obs.).

As with temperature, a history of exposure to high levels of solar radiation could also render corals more resistant to bleaching. Brown *et al.* (2000) noted that the bleaching susceptibility of *Goniastrea aspera*, a shallow-water Indo-Pacific coral (Phuket, Thailand), could be predicted from its history of exposure to solar radiation. Colonies that regularly experienced annual solar bleaching on their west-facing surfaces due to increased solar radiation in January-March were more tolerant of high temperatures during temperature-induced bleaching events in May of 1991 and 1995. Even though solar radiation measurements in May were equal on east- and west-facing sides of *G. aspera* colonies (identical temperature and solar radiation regimes were also applied under controlled conditions in the lab), colonies bleached only on their east-facing surfaces during periods of high sea surface temperatures. Sampling and molecular analysis showed that this was not due to genotypic variation among zooxanthellae on the different surfaces. Brown *et al.* (2000) concluded that west-facing surfaces of *G. aspera* may have been protected against temperature bleaching in May because their history of exposure to solar radiation conferred greater resistance to the combined effects of temperature and solar radiation.

Finally, there is some circumstantial evidence that reefs that have historically suffered from a variety of anthropogenic stressors may also be more resistant in the face of mass bleaching events. Goreau (1992) studied patterns of bleaching in relation to temperature and various anthropogenic stressors throughout the reefs of Jamaica and concluded that: 1) standard local anthropogenic stressors are not a cause of mass bleaching; and 2) corals that are routinely subject to these anthropogenic stressors appear to be less susceptible to the stressors that cause mass bleaching. In East Africa, following the 1998 event, some reefs that showed the earliest significant recovery were already severely impacted by fishing and collecting, and were in relatively marginal reef flat environments (Obura *et al.* 2000). This suggests that pre-exposure to such stresses may pre-adapt corals to faster recovery in some areas. However, it is too early to generalize, as in other areas, damage from overfishing followed by overgrowth by fleshy algae may have delayed colony and reef recovery.

Conclusions

In cases where the goal is biodiversity conservation, coral reef areas that are likely to be protected from severe bleaching and related mortality by one or more of these environmental factors should receive a high level of protection from other, direct anthropogenic stressors that managers have the ability to control at the source. The dual purpose of focusing on these areas is to maximize the conservation of biodiversity through protection of the most bleaching-resistant sites and to secure their role as sources of larvae to hasten recovery of down-current areas that are more susceptible to bleaching and thus likely to suffer higher mortality. Such down-current "sink" areas should also be managed and protected to favor conditions for maximal larval recruitment and reef recovery.

In order to implement this strategy, we must first tease apart those factors that are more or less reliable (predictable) in their presence *and* persistent (consistent) in their effects, compared to those that are unreliable and ephemeral. The former should be targeted while the latter will be of less interest for management. Further, it will be necessary to assess particular sites for operation of these factors in the context of both localized (small-scale) processes and large-scale processes that generate overlying effects on local sites. Thus, it is useful to consider the different categories of resistance to coral bleaching according to their reliability and scales of operation.

Environmental Determinants of Resistance to Coral Bleaching: Reliability and Scales of Operation

We have identified four main categories of environmental determinants of resistance to coral bleaching: water movement, upwelling, protection from solar radiation, and history of exposure to stresses. Within each of these categories, there are multiple conditions or phenomena that may afford corals some protection from anomalously high SSTs, high levels of solar radiation, or both. These phenomena are especially important where they coincide with – and moderate the effects of – ENSO events that would otherwise lead to mass bleaching in those areas. It is therefore useful to break down the various types of factors according to their degrees of reliability and scales of operation (Table 1).

Table 1: Environmental determinants of resistance to coral bleaching according to: 1) whether they operate at local or larger scales, and 2) whether their presence or operation can be considered reliable and persistent versus unreliable and ephemeral.

	RELIABLE/PERSISTENT	**UNRELIABLE/EPHEMERAL**
LOCAL-SCALE	• Water movement: tidal exchanges/ narrow channels • Upwelling: localized current-driven • Solar protection: physical objects (overhangs, tall islands) • Solar protection: turbidity (if consistent) • History: temperature stress (e.g., emergent reefs) • History: solar radiation (west-facing corals or reef sections on west-facing sides of islands)	• Water movement: wind-driven turbulence • Upwelling: localized wind-driven • Solar protection: depth • Solar protection: CDOM • Solar protection: turbidity (if storm-related) • History: direct anthropogenic impacts (e.g., destructive fishing) >> "unreliable" because we should be seeking to remove these from all protected areas
LARGE-SCALE	• Water movement: major currents and "mass island effect" • Upwelling: major currents and "mass island effect" • History: temperature stress (tolerance differences among populations at different latitudes)	• Water movement: hurricanes • Upwelling: hurricanes • Upwelling: seasonal (if can be disrupted by ENSO) • Solar protection: cloud cover

From a management perspective, it is the "reliable/persistent" category of factors that are of primary interest. Note that the breakdown is not a rigid one. Some factors (e.g., turbidity or wind-driven upwelling) could potentially be categorized as either "reliable/persistent" or "unreliable/ephemeral", depending on the particulars of the situation in a specific location. Managers should identify and strategically target "reliable/persistent" factors relevant to their own reef areas for: 1) inclusion in extended areas of strict protection in existing MPAs, and 2) determination of priority areas for zoning of additional, strictly protected MPAs. First, however, a monitoring strategy must be implemented to determine whether the identified factors are reliable and persistent and actually do afford significant protection during bleaching events.

Monitoring to Determine the Persistence and Significance of "Reliable " Factors

Ideally, we would like to identify for managers which environmental factors: 1) have a significant positive effect on coral resistance during bleaching events *and*; 2) are reliably present and sufficiently persistent through time to protect corals from bleaching during ENSO events or other *HotSpot* formations. The goal is to determine which factors should be focused on for management purposes. While "unreliable" factors will not be useful for MPA strategic planning down the line, their existence necessitates a short-term, intensive monitoring project that includes (does not ignore) this "unreliable" category of effects. This is because infrequent, unreliable environmental factors (such as hurricanes or cloud cover) could confound the results of monitoring that is designed to determine the effects of persistent, reliable environmental factors (such as local currents or shading by objects). Therefore, it is useful to consider the following points when planning the proposed monitoring program:

- To determine whether "reliable" factors do have a significant and persistent effect on resistance, we will need a detailed monitoring project that looks over multiple reef types, in multiple areas, and in multiple regions, both inside MPAs and in control areas outside of MPAs
- Large-scale, "unreliable" factors (e.g., cloud cover) that act as an overlay on the operation of "reliable" factors (e.g., physical shading) could confound the results of monitoring that is designed to detect strong correlation between "reliable" factors and resistance to coral bleaching – therefore, it will be necessary to tease apart these effects through initial intensive monitoring of all types of environmental factors
- Over the course of a multi-year project, which may include multiple bleaching events in different regions, "reliable" factors should show up as strong correlates with resistance, despite (for example) the occasional cloud system that makes all the corals equally protected and prevents detection of a benefit from (for example) shading
- Partners in the project could contribute valuable information through whatever level of monitoring that they have at their disposal
- At the lowest capacity, project partners could target and test one or more environmental factors for effects on resistance, by supplementing existing monitoring with measurements of, for example, light levels in areas of shading by physical objects – or even by providing data on coral condition that are simply broken down by whether the corals are observed to be in shaded or unshaded locations
- Partners with the capacity to implement more detailed monitoring could target and monitor the whole array of local-scale, large-scale, "reliable" and "unreliable" factors to assist in teasing apart the different effects
- A robust data set will be needed to determine the significance and persistence of "reliable" factors before it will be possible to use them as priority determinants of which reef areas to target for special protection from other impacts

Implications for MPA Management

What can managers do today?

- In the context of existing monitoring programs, census reefs both inside and outside of MPAs for the presence of reef areas with one or more "reliable local-scale" factors
- Work with oceanographers or other sources to obtain climatological/oceanographic data (including remote sensing data) in order to identify any "reliable large-scale" factors that may operate at their sites, such as major regional currents that are unlikely to be entirely disrupted during ENSO events
- Begin a process to afford higher levels of protection to these reef areas or locations
- Where possible, enhance existing – or develop new – monitoring practices to include detailed monitoring of all categories of environmental factors along with reef condition at these and at control areas or locations
- Increase careful monitoring during the next bleaching event
- In general, the goal is to monitor the condition of the corals where environmental factors of interest exist and in adjacent control sites where they have no influence, in order to determine whether there is indeed a strong correlation between these factors and bleaching susceptibility and resistance

The ultimate goal: integration of new principles into guidelines for MPA site selection and design

The Salm *et al.* (2000) guidelines for MPA planning and management include the use of various categories of selection criteria (social, economic, ecological, regional, and pragmatic) for priority ordering of sites for MPA selection and zoning. Confirmation of environmental factors that afford protection from bleaching mortality may necessitate consideration of additional site selection criteria from a new category: survivability and resistance to climate change. That is, when evaluating existing MPAs or planning new ones, MPA managers should consider site selection criteria that will allow coral communities that are reliably influenced by one or more protective environmental factors to be incorporated into strictly protected zones. Managers should also afford high levels of protection to sites down current of these to enhance larval settlement and recovery of these dependent areas.

Consequently, MPA management strategies may need to be carefully planned (or re-adjusted) for proper control and use of bleaching-resistant areas. All extractive uses should be prohibited in these areas. Some of the sites might be able to tolerate some level of visitation for research and recreational purposes. However, this will require comprehensive prior assessment and should only be permitted if, for example, moorings can be safely deployed (off the reef in sandy substrates) and enforced, and if conditions are such that scuba divers can drift along walls but not over coral, or when depths are great enough to preclude snorkelers stepping on corals. Access to these sites would need to be controlled by special measures that would prevent overuse in an equitable way, yet still provide a good source of additional revenue to finance management (e.g., licenses for tour operators could be auctioned among a group of accredited operators on the basis of willingness to pay, and divers would pay a surcharge for access to these sites). Finally, development of flexible zoning schemes could allow for strict "no-use" protections to be rapidly enacted at appropriate sites during—and some period after—bleaching events occur in the region, to allow maximal survival and recovery of affected reef areas.

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Scientific Principles for Establishing MPAs to Alleviate Coral Bleaching and Promote Recovery

Terry Done[1]

Abstract

Marine Protected Areas (MPAs) are an important management tool for protection of regional coral reef biodiversity, from genotypes through species and habitats. In the context of global climate change, the identification of suitable areas needs to take account of deterioration in ocean climate, manifest as increased frequency of major bleaching and death of corals. The distribution of discrete protected areas should ideally spread risk in relation to all non-manageable pressures – not just anomalous sea temperatures. The selection process should thus be strongly based on an assessment of all threats to local species diversity and abundance.

In relation to warming sea temperatures, the selected coral reefs would ideally have at least three of the following attributes. 1) A history of their corals not dying during past exposures to temperature regimes that are predicted for the future (indicating they are populated by heat-resistant genotypes, or 2) a low risk of future exposure to damaging heat scenarios. 3) Large areal extent and wide range of depths, and associated high diversity and abundance of coral reef species. 4) A strategic location that will maximize both a) strong and reliable recruitment of all of its species—be they from other reefs or from within their own boundaries, and b), the likelihood that a proportion of its propagules will effectively seed other areas. Ecological performance indicators for the effectiveness of the closures should focus on the maintenance or restoration of "ecosystem quality" of both individual MPA nodes, and the network as a whole. Simple measures like "percentage coral cover" are a reasonable first order indicator, but need to be standardized against expected coral cover in places where cover fluctuates widely under natural disturbance regimes. Monitoring and performance measures should be more attuned to coral demography, phase shifts, ecological processes, and functional groups

Introduction

The high likelihood that there will be increases in the climate-related frequency of sea warming events causing major coral bleaching and coral death in coming decades makes effective stewardship of coral reefs and associated habitats now more important than ever. Effective stewardship aims—within the bounds of natural spatial and temporal variability—to preserve or restore the aesthetic qualities of coral reefs and their biological diversity, their secondary productivity, their complexity and their resilience. Marine protected areas (MPAs) stand alongside pollution control and fisheries management as key tools for stewardship. This paper is a contribution to the workshop "Mitigating Coral Bleaching Impact through MPA Design," sponsored by The Nature Conservancy and the World Wide Fund for Nature, in Honolulu, May 29-31 2001. The Workshop's objective was "To develop science-based principals to guide establishment of Marine Protected Areas (MPAs) to mitigate coral bleaching and related mortality and optimize conditions for reef recovery."

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MPAs may be strict "no take" zones, or they may be larger "multiple use protected areas," with or without included "no take" zones, (or Highly Protected Areas; Day *et al.* in press). Multiple use, while exposing the effectiveness of the large MPA to the uncertainties and risks of fisheries management, offers the significant benefits of inclusion of key stakeholders. Those fishers and tourism operators who are convinced about the role of biological diversity and proper ecosystem function as the foundations for their enterprise can be the most committed advocates for conservation of MPAs. It is a strong incentive for them to lobby hard to protect marine water quality, and to develop and implement world's best practice for ecological sustainability in their own operations.

Putting aside social and cultural considerations for the present, the perfect regional configuration of MPAs would be one:

- which included the full suite of regional biological diversity in reef coral communities; and,
- in which each protected area MPA displayed a "tolerance" response to all future climate-related stress (Done 1999).

In this outcome, the individual organisms that are exposed to the elevated heat stress episode acclimatize, and there is no episodic change in local biological diversity, species composition or demographic structure. The poorest selection, should we knowingly make it when we knew there was a better choice, would be to include a place that would display a "phase shift" response. This is where the key functional "reef-building" groups of corals and coralline algae are killed off and displaced for extended periods (decades, not just years) by seaweeds (undergrazed systems - Hughes 1994) or substrates that are eroded so fast that no significant biomass accumulation is possible—even fleshy algae, let alone coralline algae or corals (overgrazed systems - McClanahan 1994).

Observations following the global bleaching event of 1998 indicate some coral reef regions were unaffected, and some were badly affected. High proportions of coral were killed across a wide range of species and ages. However even within affected regions, bleaching impact was heterogeneous in space. Some reefs escaped with no discernible damage because local oceanography and topography prevented overheating (Skirving *et al.* 2000). Within severely affected reefs, there were parts of the reef with little damage (T. Done, pers. obs.; R. Salm and G. Llewellyn, pers. comm.). Within the severely affected parts, even those with high mortality and algal invasions, heat-hardy corals did survive, including both old adults and juvenile corals (T. Done pers. obs.). The latter, though exposed to heating in their first year of life, may have survived because they were only pinhead or fingernail-sized spat that had yet to take on board a complement of zooxanthellae. This latter observation underscores the importance of MPA planning that accommodates long-distance larval dispersion, so that when a future bleaching year does come along, these small azooxanthellate corals are already in place to ensure an early start to coral recovery.

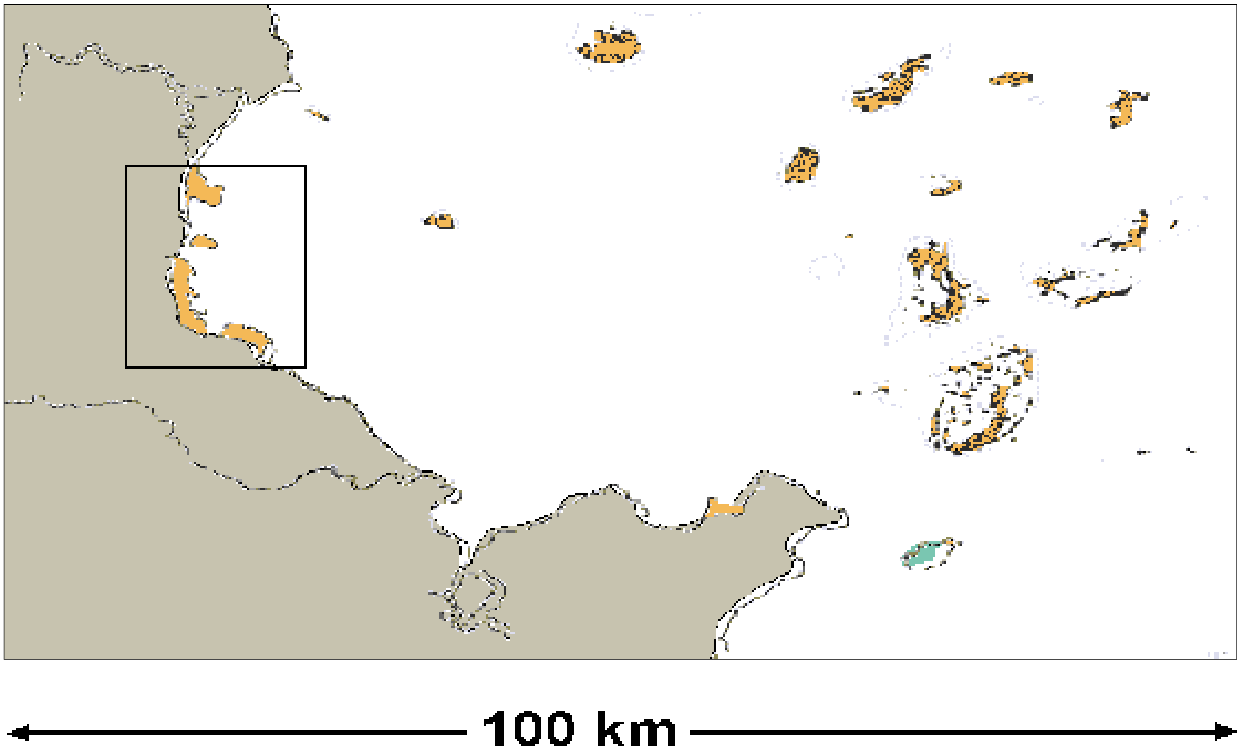

Fig. 1. Effects of scale on approach to designation of Marine Protected Areas. At local scales (inset), it is possible to have undertaken comprehensive biodiversity and condition assessments of most reef areas. At the regional scales, only a sample may be surveyed, and assessments of reef types, reef condition and the distribution of threats will involve more extrapolation from more limited assessment relative to the size of the area.

However there are likely to be some poor choices made in this approach, because these "best" sites may include two classes of reefs: those that were not exposed to elevated sea temperatures ("B" in Fig. 2), and those that were exposed, but nevertheless survived ("C"). The former would be a good choice if their lack of exposure was due to a reliable oceanographic feature such as current or upwelling that makes prolonged exposure to lethal temperatures unlikely, even in a warmer world. It would not be so good if the cooler water body just happened to advect onto the reef that year, but in the longer term was not a reliable oceanographic feature.

A more detailed analysis would be required to make choices among sites that appear equally suitable in terms of current biodiversity and abundance of reef species and habitats. Coral reef areas included within a network of MPAs would ideally have at least three of the following attributes. 1) A history of their corals not dying during past exposures to temperature regimes that are predicted for the future (indicating they are populated by heat-resistant genotypes, or 2) a low risk of future exposure to damaging heat scenarios. 3) Large areal extent and wide range of depths, and associated high diversity and abundance of coral reef species. 4) A strategic location that will maximize both a) strong and reliable recruitment of all of its species – be they from other reefs or from within their own boundaries, and b), the likelihood that a proportion of its propagules will effectively seed other areas.

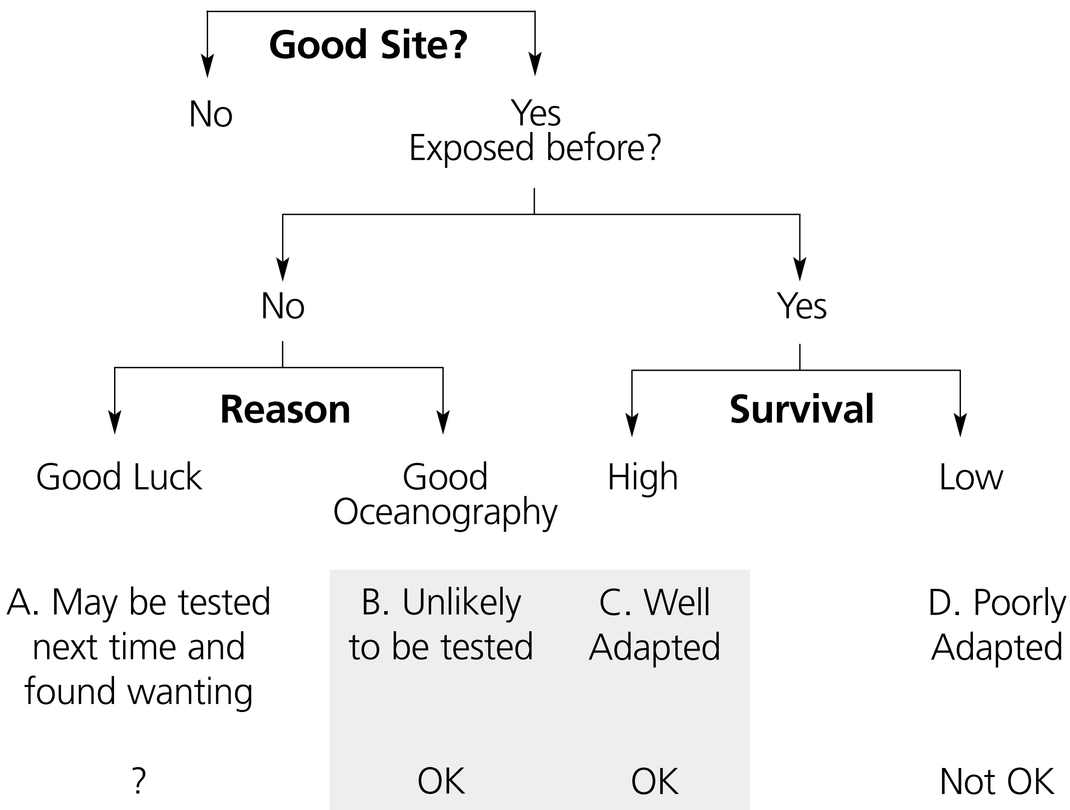

Fig. 2. Two ways in which a reef that rates well for biodiversity values may be suitable (OK) for MPAs in global warming scenario.

The identification and evaluation of reefs against these attributes can be undertaken through a spatial risk assessment approach. This approach is being undertaken in a collaborative study between AIMS, the Great Barrier Reef Marine Park Authority, and NOAA. Those reefs at that are at most (Attribute 1) or least (Attribute 2) risk of exposure to bleaching temperatures can be identified using satellite remote sensing, temperature loggers and physical models of heat in reef waters (all to resolutions of <0.5°C and 1 km^2). Time series of satellite imagery of sea surface temperatures (SSTs) can help identify sites that are reliably cooled, and those that are not. This exercise can help identify those reefs that were exposed to elevated SSTs, but whose corals nevertheless survived. Such places may be the best choice of all because, despite exposure to elevated temperatures, those coral and zooxanthellae genotypes that survived are by definition, more heat resistant. In an ideal world, such reefs would be key "source" reefs in a network of MPAs. Evaluating reefs in terms of their intrinsic biodiversity quality (Attribute 3) would require field work and rating of survey sites in terms of ecosystem quality indicators (Done 1995; Done and Reichelt 1998; DeVantier *et al.* 1999). For the degree to which a reef's location is "strategic" in respect to its relative strength as a source and sink (Attribute 4), a review of available oceanographic data at peak spawning periods could be undertaken, complemented by development of connectivity matrices based on hydrodynamic modeling if necessary.

We are trying to more formally characterize risk of bleaching in the Great Barrier Reef. Field observations of bleaching in 1998 (Berkelmans and Oliver 1999) and high resolution (1 km) SST images derived from the NOAA AVHRR satellite (Fig. 3) indicate there is considerable spatial variability in temperature at scales below 10 km, and we are trying to understand patchiness at these finer scales. This is being done through characterization of the SST patterns seen in AVHRR images (e.g., Fig. 3), and hydrodynamic modeling of the likely physical processes causing them (W. Skirving in prep.).

Dose-response curves for temperature exposure have been determined for representative reefs using field observations—e.g., from 1998 and for indicative coral species (R. Berkelmans in prep.).

Mitigating the future effects of global climate is, of course, only part of the exercise of creating MPAs that effectively protect reef biodiversity. The Great Barrier Reef Marine Park Authority (Day *et al.* in press) has developed a process for identification of prospective highly protected areas (HPAs) that is guided by notions of representativeness, risk spreading, and connectivity. Biodiversity representativeness is approached through "bioregionalization," and risk spreading and connectivity through replication and systematic separation of HPAs along the main current streams within and across bioregions.

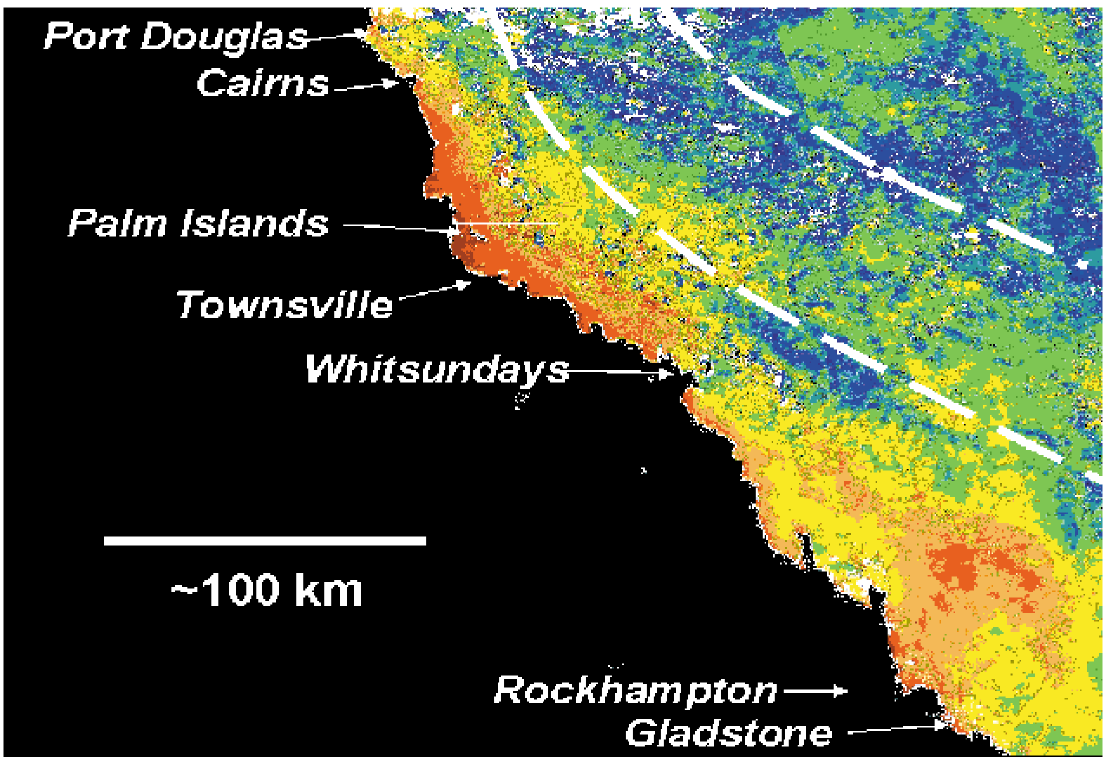

Fig. 3. AVHRR image of sea-surface temperatures showing heating in the shallower waters close to the coast of Queensland, and cooler water on reefs far offshore between the white broken lines.

Bioregionalization: Bioregionalization is a process of division of the entire map into contiguous blocks of reef and/or adjacent areas that are occupied by "groups of animals and plants and… physical features that are… distinct from [those of] surrounding areas" (www.gbrmpa.gov.au/rap). Individual bioregions are large—far transcending the detailed variation among zones within individual reefs. Rather, they group adjacent reefs whose overall structure and zonation is qualitatively the same. The bioregion's seafloor, itself likely a mosaic of benthic substrata and communities spread over gradients in depth and environment, is nevertheless just one mosaic, and just one range of depth and environmental gradients. The definition of bioregions relies on experts being prepared to extrapolate and interpolate usually sparsely distributed field observations, and to draw "fuzzy" boundaries between bioregions. Always in mind in this process is the notion, if one takes any slab of this bioregion, it should represent the biodiversity of assemblages, structure and environment as well as any other.

Highly protected coral reefs should ideally be embedded within larger protected areas that encompass adjacent habitats and are representative of the larger "bioregion" of which it is part—the area where plant and animal assemblages and physical features are distinct from adjacent areas. Contiguous habitats are protected for their own sake, and also because non-reef habitats such as sea floor, water column, and mangrove areas may have some functional connection to the coral reef, such as provision of nursery areas, spawning aggregations, or feeding areas.

Risk spreading: The intent of "risk spreading" is to insure against the entire biodiversity in the MPA becoming severely compromised at any one time by some broadscale, unmanageable impact of short duration but large area of impact, such as hurricane waves, flood plume, bleaching event, or crown-of-thorns outbreak. The solution was to specify a number of replicate MPAs dispersed widely throughout each bioregion.

Connectivity: The idea of "connectivity" was accommodated by specifying that the replicate areas as far as possible be arranged along the direction of prevailing currents at spawning time, which is essentially parallel to the Queensland coast in the context of the GBR.

How much? A flat percentage of bioregion area to be designated as candidate HPA was specified, based on an (untested) assumption that this would protect viable population sizes.

"Must have" areas. A geographic information system model (Day *et al.* in press) is used to generate maps of "candidate areas" using rules on the number of replicates, percentage area to be protected, boundary smoothing and orientation. The bioregions (100s to 1000s of km^2) are divided into "management units" (whole reefs and, for the sea floor, hexagon units either 10 or 30 km^2 depending on assumed "grain size" of biodiversity patchiness). Twenty or so different maps are generated from the one set of rules, and overlay techniques are used to generate maps of the frequency of inclusion of each management unit in an HPA. Those with high frequency are highly "irreplaceable" in terms of the analytical rules supplied, and would be areas to fight hard for as HPAs, assuming the rules have adequately captured the biodiversity conservation need. By contrast, management units scored as having low irreplacability are more easily traded off where such areas are valued highly for other purposes such as fishing.

Discussion

MPA design and selection can benefit from insights from a range of scientific analyses: coral reef ecology, coral physiology, larval biology, physical oceanography, coastal hydrology and satellite remote sensing. In the global climate change context, there is the added challenge of interpreting vulnerability of prospective MPA sites based on past performance during major bleaching events, and of downscaling coarse resolution global and regional climate models to assess which reefs may be least vulnerable in, say, 2020 or 2050.
The science will be far from perfect, and any proposition to create MPAs (i.e. deny people access or resource use) needs to be carefully managed. Acceptance and implementation by the broader community of any MPA proposition from any scientifically informed advocate for nature conservation (e.g. government agency or conservation group) requires careful attention to the diverse community needs and expectations, and to the nature and timing of their involvement in the process (Day *et al.* in press). Sympathetic presen-

tation of a clear, well considered and socially sensitive case is a key step in the development of community "ownership", and it is vital this engagement take place neither too soon or too late. Too soon, and "science hasn't got its act together": too late and its "now they tell me they want to take away my access".

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Lessons Learned from the Intensification of Coral Bleaching from 1980-2000 in the Florida Keys, USA

Billy D. Causey[1]

Historical Background

Observations of coral bleaching in the Florida Keys have been reported in the scientific literature since the 1980's (Jaap 1984). Most of the early reports were associated with a combination of stressful events, such as cold water stress due to winter fronts, brief warm water events, or reduced light penetration during lengthy turbid water events in the late 1970's (personal observations). In August of 1984, corals were observed and documented to bleach due to extended shading of the coral colonies under the hull of a grounded 460' ship, the *M/V Wellwood*, on Molasses Reef in the Key Largo National Marine Sanctuary.

The periodic short-term coral bleaching events that were observed and reported in the 1970's were more than likely preceded by other such episodes in the 1960's, 50's and probably since man began studying coral reefs. My personal experience with the biology and ecology of coral reefs began on the coral reefs off Vera Cruz, Mexico in 1963. As an undergraduate, I participated in several fieldtrips each year to dive and study the Mexican coral reefs. To my knowledge and recollection we never observed nor recorded extensive coral bleaching between 1963-69. However, an obvious pattern of intensification of coral bleaching and other marine perturbations has occurred throughout the 1980's and 1990's in the Florida Keys.

Sponge Die-off – 1979. In mid-summer (June-July) of 1979 I began observing a massive die-off of the Barrel Sponge, *Xestospongia muta* off the Lower Florida Keys. In an area along the reef tract due south of Big Pine Key, Florida, literally hundreds of large, old barrel sponges were observed to be disintegrating and falling apart. The sponges exhibited various stages of decay, with some being totally dead and others being slowly dissolved with only the siliceous skeleton remaining in place. This die-off continued for over a month. The State of Florida Department of Natural Resources (DNR) sent a sponge biologist to the Keys to go out with me and take tissue samples of the various stages of the sponge blight.

The area along the reef tract where the sponge die-off was most apparent was due south, or directly seaward of the large tidal passes that connect the more sub-tropical waters of Florida Bay or Gulf of Mexico with the more tropical waters of the Atlantic Ocean, supplied by the Florida Current. Our extensive knowledge of water circulation in the area (Smith and Pitts 1993) that has been documented since the die-off has documented that the net flow of the bay water and inshore water is in the direction of the outer coral reef tract.

At the time of the die-off, it was my anecdotal observation that the water mass from the bay and inshore areas was affecting the health of the barrel sponges. Water circulation studies conducted in the mid-1980's (Smith and Pitts 1993) demonstrated that a hydrological linkage existed, but without real-time monitoring of hydrographic parameters in 1979, my observations stand without scientific validation.

Massive Fish Die-off – 1980. In June and July 1980, another marine perturbation took place in the Florida Keys. About mid-June doldrum-like weather patterns replaced the normal summer trade winds in the Florida Keys. The skies remained clear and almost cloudless and the seas were slick calm for over six weeks. After only a couple of weeks of these weather patterns, my wife and I began observing reef fish showing

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signs of extreme stress. Angelfish were observed to be oriented vertically in the water column, struggling to swim vertically, while respiring at very high rates. Their opercula were pumping rapidly and their behavior was unlike anything we had ever observed in the open ocean. We had observed such stressful behavior by fish in closed aquariums in the past.

Other observations of fish behavior were equally distressing during this timeframe. We observed surgeonfish lying on their sides on the open sand bottom and gasping. Parrotfish were scratching their sides against the substrate as if they were exhibiting the early signs of Ich or other fish diseases that are commonly observed in marine aquariums when fish are under stress. Butterflyfish and angelfish were observed to have large open wounds on their sides and were extremely stressed. We collected some of these stressed fish and transported them to our closed holding tanks. The fish immediately responded positively to the cooler water, following a routine acclimation period. My wife was able to treat the open wounds and we lost very few of the fish. They were eventually returned to open water after the stressful conditions subsided.

After a couple of weeks of these observations, large numbers of fish began dying-off throughout the Keys. Reports of the die-off started coming in from the public from Key Largo to Key West. Most of the observations were restricted to the offshore reef tract. Wind rows of dead reef fish were reported.

The slick-calm, doldrum-like weather patterns persisted for approximately six weeks with a resultant massive fish die-off unlike any I have ever observed in the Florida Keys. I contacted DNR biologists about the event and before they could mobilize to come to the Keys, the die-off had ended and the weather conditions had returned to normal for the season.

We observed minor coral bleaching of offshore coral colonies during this event. Coral colonies appeared mottled and off-color, or lighter in color than normal. There was no uniform bleaching during this episode.

Long-spined Sea Urchin Die-off – 1983. The long-spined sea urchin, Diadema antillarum was first observed to be dying-off in the Florida Keys in July 1983. Dr. Harris Lessios from the Panamanian Smithsonian Lab, who first observed the die-off in January 1983 at some of his study sites off Panama, tracked the event across the Caribbean.

In June of 1983, participants in a workshop of Florida Keys coral reef managers (past and present) with two decades of experience in coral reef management in the Keys, exclaimed about the abundance of *Diadema* at Looe Key Reef as compared to past years. Some observers estimated counts of 3000-4000 urchins per side of a single coral finger. At the time of the workshop, we had not been alerted to the die-off that had begun in the lower Caribbean in January of that year. Ironically, by the end of July 1983, one could not count but a few *Diadema* during a full single tank dive in the Fore Reef at Looe Key.

Dr. Lessios was able to take samples of *Diadema* tissues at every stage of stress during the event in the Florida Keys but was unable to isolate a causative factor such as a pathogen.

Coral Bleaching – 1983. In July 1983, slick-calm weather patterns, doldrum-like conditions, returned to the Florida Keys. At the time we were still assessing the die-off of *Diadema* at Looe Key National Marine Sanctuary, the corals began going off-color and turning white after only a couple of weeks of these weather patterns. Walter Jaap and Jennifer Wheaton of DNR had initiated a study of the corals (soft and stony) in the Looe Key NMS and were in the early stages of their work when the corals began to bleach.

Soon we learned the coral bleaching was not just isolated to Looe Key Reef but spread along the coral reef tract from Big Pine Key to Sand Key Reef off Key West. The coral bleaching was observed to be isolated to the outer reef and affected the shallow Fore Reef habitats the most. The deeper transitional reefs that lie about 15-20' deep and like a thread, connect the shallow spur and groove reef formations from off Key West to Key Largo, were not observed to be as bleached.

The 1983 coral bleaching event was geographically restricted to the outer shallow reefs in the lower Florida Keys. Again, more recent water circulation and current studies have shown that the net flow of water is from the Gulf and Florida Bay offshore, in the direction of the reef tract. Additionally, water circulation and current studies have shown that the water heads to the west, inside the reef tract and in an opposite direction of the easterly flowing Florida Current. This current pattern baths the coral reefs along the reef tract from Looe Key Reef to Sand Key with the warmer waters (in the summer) of the Gulf and Florida Bay. As these waters move through the inshore waters they pick up nutrients from storm water runoff and waste water, as well as carrying other pollutants and water quality problems that run into the nearshore or coastal waters of South Florida and are carried to the Keys.

Walt Jaap conducted an assessment of the corals during and after the bleaching event. He found only a 3-5% mortality of the corals during the event. This had been the first wide scale coral bleaching event that I had observed in my 15 years of visiting and living in the Florida Keys. The shallowest portions of the Fore Reef habitat appeared as though a snowfall had taken place. The corals were stark white for a period of nearly two months and began recovering their color in October1983.

Black-Band Disease – 1986. Prior to the Spring and Summer of 1986 I had searched considerably for examples of coral diseases to photograph for a slide file. I had little success finding an example of black-band disease until May 1986. In May 1986, Harold Hudson, a coral biologist, and I observed an alarming outbreak of black-band disease on coral colonies in the Fore Reef at Looe Key Reef. Along a distance of approximately 150 meters I documented over four dozen infestations of black-band disease on coral colonies of all sizes. Harold Hudson established a monitoring program for the black-band outbreak and documented a rate of mortality of the coral tissue at 3mm per day. That summer I witnessed 200 year old die as a result of the black-band outbreak.

Between the summer of 1986 and early 1990's black-band disease outbreaks were reported along the entire coral reef tract, from the Biscayne National Park all the way to the Dry Tortugas National Park. The black-band disease affected both inshore coral colonies as well as offshore coral colonies. The coral disease was at its' peak of infestation in the warm months of the spring and summer.

Coral Bleaching – 1987. In June 1987, doldrum-like, slick calm weather patterns reoccurred in the Florida Keys. After a week or so of these conditions I called my staff together at the Looe Key National Marine Sanctuary and asked them to start watching for signs of coral bleaching if the slick calm conditions persisted. On July 14, 1987, while on a site visit to Looe Key Reef, a colleague and I began observing coral bleaching. Some of the coral colonies had turned mustard yellow while other colonies were mottled in coloration or slightly off-colored.

By mid-August the corals in the Fore Reef and deeper coral reef habitats were bleaching. The dive charter captains and other visitors to the reef began calling in reports of coral bleaching. We continued to monitor and photo-document the coral bleaching event with the belief that it was an isolated and short-term episode like the 1983 bleaching event. However, by early September we began receiving reports of coral bleaching from throughout the Florida Keys. By the latter part of September reports of coral bleaching were pouring in from all over the Caribbean. By mid-October reports of coral bleaching in the Indo-west Pacific were being circulated among coral reef managers and scientists. Coral bleaching had become a global, synchronized event.

Like the 1983 bleaching event, there was little mortality of the corals observed, but a comprehensive, Keys-wide monitoring program was not in place to detect changes in the health of the corals and the level of living coral tissue. Several small-scale monitoring programs did exhibit a considerable amount of loss of living coral tissue during the timeframe, but the losses were not directly linked to coral bleaching.

The primary significance of the 1987 bleaching event in the Florida Keys compared to the 1983 event was the broad geographical extent of the coral bleaching along the outer reef tract throughout the Keys. It was also significant that the bleaching affected corals at greater depths, but still restricted to the outer reef tract. The corals from very shallow water out to depths of over 30m were almost uniformly white.

The waters remained so calm for such a long period of time, a mat-like blue-green algae (perhaps a *Cyanobacteria*) grew across open stretches of sand bottom. The sand bottom was almost uniformly covered by dense mats of algae in areas where normally wave action would have kept the sand moving and prevented the growth of the algal mats.

Minor Coral Bleaching – 1989. In 1989, I observed a minor bleaching event at Looe Key Reef. The bleaching was restricted to a single genus of coral. The bleaching affected only species of Agaricia and was geographically limited to the Fore Reef at Looe Key Reef. The event, which began in August, only lasted about six weeks and did not seem to result in coral mortality. The most significant circumstance about this bleaching event besides it being restricted to a single genus was that I received reports of bleaching of the genus Agaricia from Puerto Rico and Lee Stocking Island in the Bahamas. Only a single genus was affected in those areas.

Coral Bleaching – 1990. In mid-July 1990, doldrum-like weather patterns with slick calm seas returned to the Florida Keys. Early signs of bleaching conditions began to appear, such as the zoanthid, *Palythoa caribaeorum,* which turned pale white and the polyps completely closed shortly before the stony corals bleached. By the first week of August the corals began to bleach along the outer reef tract with observations first recorded at Looe Key Reef. By the second week of August the coral bleaching was being observed on the inshore patch reefs and coral colonies in the tidal passes. This was the first time a coral bleaching event had extended to the inshore waters. The Sanctuary office began receiving calls from the general public who were concerned about the bleaching corals.

The shallow reef coral colonies had Looe Key Reef were severely bleached for two full months. We established several 10m monitoring transects along the reef crest and for the first time recorded substantial loss in living corals as a direct result of the bleaching. Over 65% of the fire coral *(Millepora complanata)* along the shallow reef crest died as a result of this bleaching event. This amount of loss was anecdotally observed on other shallow reefs from Key Largo to Key West but was not measured. This was the first time a large amount of coral loss could be linked directly to coral bleaching.

The significance of the 1990 coral bleaching event was that it was the first time the corals in the nearshore waters had been broadly affected by a bleaching episode and it was the first time large levels of coral loss had been recorded as a direct result of the bleaching.

The nearshore coral reefs have acclimated over geological time to a broader range of temperature shifts and have therefore existed at higher and lower water temperatures than the offshore corals. One could assume that the upper thresholds of adapted or acclimated tolerance by the inshore coral colonies was exceeded in the 1990 bleaching event as compared to earlier bleaching episodes described above.

Coral and Fish Diseases – 1993-94. Although there was not a massive coral bleaching event reported in the Florida Keys between 1990 and 1997, coral scientists did observe wide-spread outbreaks of various diseases that were affecting both branching species of corals *(Acropora, sp.)* as well as species of boulder corals *(Diploria, Montastrea, etc.)*. The Acropora species, especially Elkhorn Coral *(Acropora palmate)*, were most affected by the disease outbreak and large amounts of living coral tissue was lost as a result of various reported diseases (e.g. white band, white plague, white plague type II, etc).

Additionally, there were reports of fish disease outbreaks during this timeframe. The symptoms and species affected very much resembled the fish die-off of 1980 that I described above.

Coral Bleaching – 1997. In July 1997, doldrum-like weather conditions returned to the Florida Keys. By mid-August a massive coral bleaching event was underway. Once again, the bleaching was widespread and heavily impacted the inshore corals. It was a particularly noticeable episode for me for I received calls from long-time residents of the Keys who were reporting they had never observed such an event. One very knowledgeable multi-generation *Conch* (person born and raised in the Keys) called me and reported he had observed massive coral colonies in the tidal passes west of Key West that were severely bleached. In all of his years of diving in the Keys, he had never witnessed such an event, nor had he heard of such extensive coral bleaching. It was his opinion that the corals he had observed were dead. There was no way of documenting the mortality, but I viewed his observations as important and noteworthy.

The significance of the 1997 coral bleaching event was it's geographical extent, both offshore and inshore, as well as the long duration of the bleaching episode. Coral colonies remained bleached or mottled in color well into 1998. I observed bleached corals in January of 1998. In previous years the bleaching had subsided by November.

Coral Bleaching – 1998. We never had much of a winter between 1997 and 1998. The unseasonably warm water of late 1997 carried into the spring of 1998 with little cooling. The doldrum-like weather patterns set in early in 1998, but unlike previous years the warm water persisted even when wind would pick up from time to time.

This was the first time we experience back-to-back coral bleaching events in the Florida Keys. Like the 1987 and 1990 episodes, the 1997-98 bleaching events were local, regional and global in scale. In 1998, you may recall the devastating reports of coral bleaching off remote islands in the Pacific. As reports of severe coral bleaching came from the Pacific, we were just starting to assess the impact of the Keys coral bleaching events of 1997-98 when the Florida Keys were hit by a hurricane and a tropical storm.

Although we have had a comprehensive coral monitoring program in place for 5 years, it has been difficult for our scientists to determine if our loss in live coral cover is from the bleaching episodes, water quality degradation, or physical impacts. However, I think is safe to assume that since scientists around the world were reporting loss of living corals due to coral bleaching, that the Keys which had experienced an unprecedented set of back to back years of stressful and long-term bleaching, had considerable loss of corals due to bleaching.

Decrease in Live Coral Cover. In 2000, our coral reef scientists have reported as much as 30% decline in living corals at some reefs. This high percentage of loss is extremely alarming to scientists and managers alike. While it is difficult to separate the causes of the coral mortality, it goes without saying the unusual perturbations that I have described above have to be taken into consideration for the successful management of coral reefs.

Use of Coral Bleaching in MPA Design

At first, I was skeptical about how we could use coral bleaching as a tool in the design or sitting of marine protected areas. As I searched my files and reference materials to write this comprehensive assessment of coral bleaching in the Florida Keys, I could not help but think of various ways coral bleaching episodes could be used in the design of MPAs.

As I have described in this assessment, I highly suspect the bleaching episodes have been intensifying over the past two decades on local, regional and global scales. I also suspect the pattern of thresholds being exceeded by each coral bleaching event will help us determine spatial and temporal criteria to use in designing and sitting MPAs.

If I use the Florida Keys as an example, I can describe patterns of coral bleaching over the past two decades, recognizing the geographical extent has increased, as well as the duration of the events. Corals that have existed in a broad range of physical conditions have now been pushed to their upper limitations of water temperature. Those corals that have survived the bleaching episodes are perhaps more adapted to the broad ranges of physical conditions experienced thus far. Perhaps it's their genetic make-up or perhaps there is a more simple explanation, but it remains obvious that the healthier and more hearty corals should be included in an MPA design.

Other suggestions would be to locate MPAs in areas where the corals could be protected from adverse conditions. For example, I stressed several times in this assessment that the corals at Looe Key Reef were the first to show signs of bleaching in 1983,87, and 90. This was not because it was where we were looking, for we were monitoring the entire reef tract. Looe Key Reef lies directly in the outflow of warm water from the Gulf of Mexico and Florida Bay. The stress of this warm water has been pushing the corals ability to adapt beyond their immediate capabilities to acclimate.

Conclusion

Coral reefs are under assault from a variety anthropogenic and natural perturbations worldwide. Whether the cause of coral bleaching is linked to global climate change in my mind is no longer a matter of debate. However, whether the causes of global climate change are of an anthropogenic source or not is subject matter for another debate. It is my opinion, that as coral scientists and managers we need to immediately take every action possible to preserve and conserve the coral reef resources of the world.

A decade ago there was much debate about whether or not coral reefs were on the decline. Today, that is no longer the topic of debate. Over 10% of the world's coral reefs have been lost to diseases, coral bleaching, pollution, and overfishing. While I don't consider myself an alarmist, I do consider myself wise enough to realize we must take action at local, regional, and global scales if we are to save our coral reefs for future generations.

Measurement and Monitoring, Methods and Applications to Coral Bleaching: Methods and Findings of the Hawaii Coral Reef Monitoring Program (CRAMP)

Paul Jokiel[1]

Coral reef monitoring programs range in complexity from purely volunteer "no cost" efforts to well-funded university/government programs. CRAMP is an example of the latter—an integrated regional program that employs state of the art technological innovations not generally available in developing countries. At the high end of the scale such regional programs cost from US$300K to $1000K annually and depend on local availability of highly trained scientists and graduate students and on a high degree of local technical support.

Ideally, investigations of coral bleaching should be viewed in an ecological context in which numerous interacting factors may contribute to the bleaching phenomena and to eventual reef decline. The CRAMP experimental design addresses such subtle issues. CRAMP was initiated in 1998 in response to increasing environmental problems being faced by researchers and managers in Hawaii. A major limitation had been the absence of a comprehensive coral reef research and monitoring program and consequently the lack of information on environmental changes on our reefs. CRAMP is an integrated statewide program designed to describe the spatial and temporal variation in coral reef communities in relation to natural and man-made disturbances. The design is such that CRAMP can address environmental questions from the local to the global scale. At the local level, CRAMP is designed to identify changes at selected sites. Viewed from a broader perspective, CRAMP can describe statewide environmental trends. CRAMP experimental design allows local scientists to investigate global changes through collaboration with other regional monitoring programs.

The CRAMP monitoring design includes sites focused on questions concerning a wide range of acute and chronic impacts. Degradation of reefs in many areas of Hawaii continues due to increasing human population and human activity. Impacts affecting Hawaiian coral reefs include; overuse (over-fishing, anchor damage, ship grounding, diver damage, etc.), sedimentation, nutrient loading, coastal construction, urbanization, catastrophic natural events (storm wave impact) global warming (bleaching), and introduced species invasions.

General Experimental Design - "Problem Focused" Research

CRAMP experimental design allows detection of changes that can be attributed to various factors such as overuse (overfishing, anchor damage, aquarium trade collection, etc.), sedimentation, nutrient loading, catastrophic natural events (storm wave impact), coastal construction, urbanization, global warming (bleaching), introduced species, algal invasions, and fish and invertebrate diseases. The experimental design provides vital information on all of the above issues, but the emphasis is on the major problems facing Hawaiian coral reefs as listed by managers and reef scientists during workshops and meetings held in Hawaii during 1997-1998. These are: overfishing, sedimentation, eutrophication and algal outbreaks. CRAMP experimental design gives priority to areas where baseline data relevant to these issues were previously collected. CRAMP continues to synthesize existing data into the experimental design, and conduct further work in order to test hypotheses concerning the role of various environmental factors in the ecology of coral reefs.

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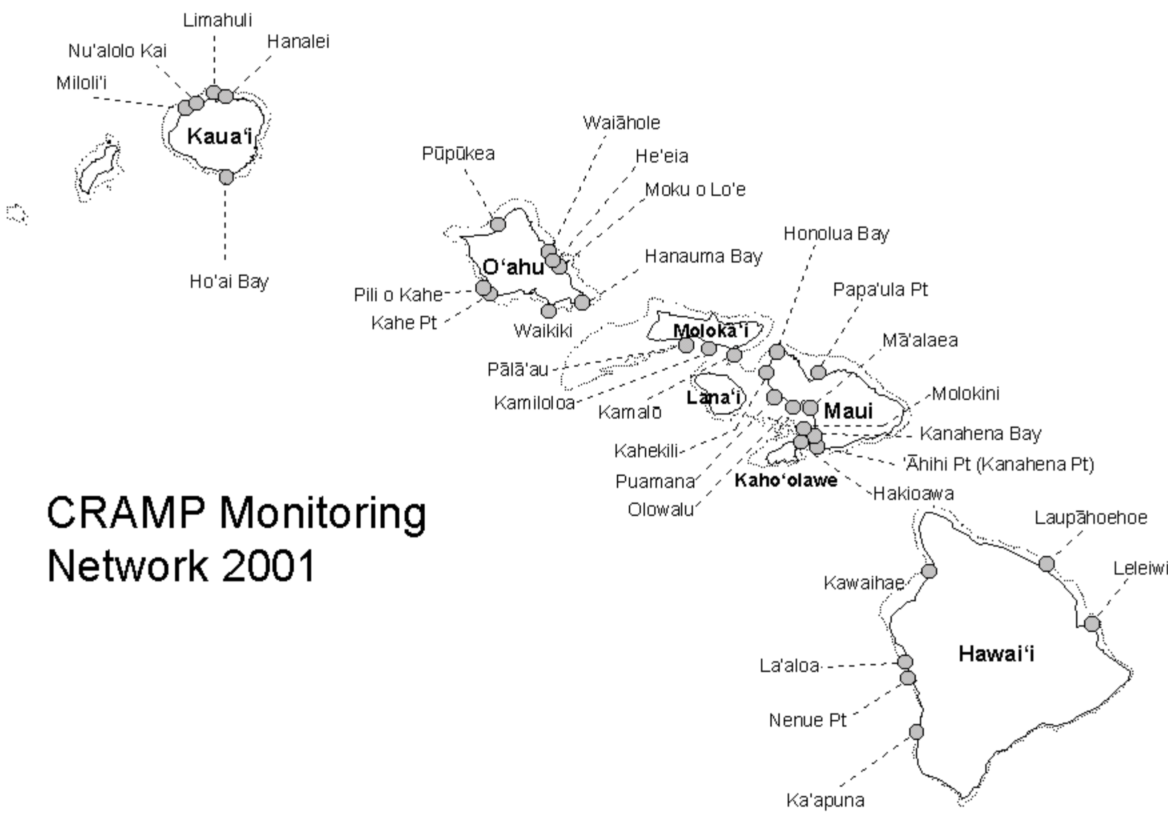
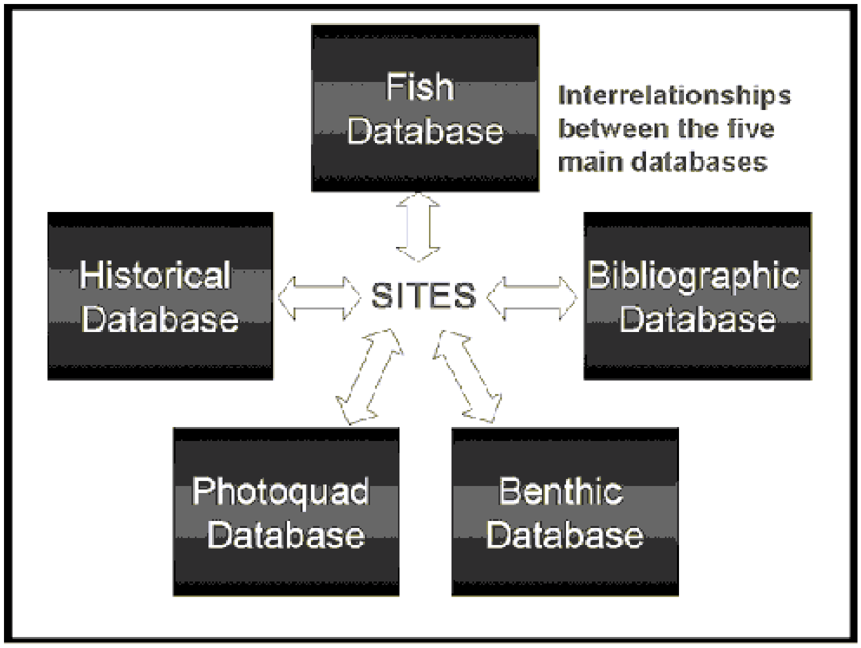
Research Sites - CRAMP has installed and initiated monitoring at 30 research sites on Kauai, Oahu, Maui, Molokai, Kahoolawe, and Hawaii. The overall network provides an excellent cross section of reefs across the main Hawaiian Islands with regard to habitat type, degree of environmental degradation due to various human and natural factors, and rates of recovery in damaged areas.



Survey Techniques - Each research site consists of ten transects and five photoquadrats at two depths (3m and 10m). CRAMP employs several methods to address changes in overall coral/algae cover and growth, as well as measurement of recruitment and mortality of the corals. Digital video is used to record images along each benthic transect for later image analysis and archiving. The protocol detects changes in coral coverage of less than 10% between samplings with high statistical power. Fixed benthic photoquadrats are used to examine trends in growth, mortality and recruitment of individual organisms. Five randomly selected permanent photoquadrats along the 3 meter and 10 meter depth contours were established with stainless steel marker pins at each corner to ensure accurate repositioning of the frame during subsequent resurveys. Sediment samples are taken at each location, and other parameters such as rugosity, depth, slope and wave exposure are also measured. Reef fish are quantified along the transect (four belt transects of 5m x 25m). This standardized protocol produces data on fish diversity, abundance and biomass. Meteorological data, adjacent land use information, water quality records, and other data are available at most sites from various sources.



Database - Recent advances in computer and communications technology enables CRAMP to collect, process, and summarize data in a form readily available to researchers and managers. Perpetuity of the database and easy access are insured through redundant archiving of information in systems with expected longevity. The CRAMP database system is can be queried to analyze and generate information from spatial and temporal data.

The CRAMP Survey and Bibliographic Database evolved considerably over the first 2 years of the project. The final form of the CRAMP database will eventually be a web-based GIS compatible system. This aspect is under technical development. The five major elements of this database system presently exist as separate database entities and are operational at present. Ultimately these will be linked through the CRAMP sites in the following manner:

The five database elements shown above contain the following information:

1. Fish Database: Consists of information on sites, taxa, surveys, and survey data (both from the past and from on-going projects). Monitoring information includes data on abundance and size estimates for fish species present at each study site.
2. Benthic Database: Consists of information on sites, taxa, surveys, and survey data (both from the past and from on-going projects). Monitoring information includes coverage data on coral, algae, and other invertebrates at study sites.
3. Photoquadrat Database: Consists of information on growth, mortality, and recruitment of sessile benthic organisms.
4. Bibliographic Database: Consists of a bibliographic ID field linked to the survey reference information table, species, keyword and location information fields, bibliographic information, publication abstract where possible, and links to or the full text of publication. The bibliographic table is continually expanded to cover pertinent publications and unpublished documents and reports.

5. Historical Database: Consists of fields that contain additional site information from previous historical collections at study sites throughout the state. This includes not only the CRAMP sites but also sites surveyed by other researchers and consulting companies.

Accomplishments:

1. During the first two years of operation CRAMP met the challenge to develop and implement statistically valid survey techniques for detecting change in benthic and fish communities in Hawaiian waters. This involved installation and quantification of transects at over 30 monitoring sites in the State of Hawaii. CRAMP completed the first cycle of monitoring and data analysis and began the second cycle.
2. CRAMP has designed and implemented a well-designed database that will allow rapid access to a very large amount of data being taken as part of the project. In addition, the database includes bibliographic and historical data for Hawaiian waters.
3. CRAMP is now in position to evaluate short-term impacts of episodic events.
4. CRAMP is positioned to evaluate long-term effects of global warming (bleaching), CO_2 impact on calcification, nutrification, sedimentation, etc.
5. CRAMP will continue to monitor the completed network with increasing emphasis on integration of monitoring activity with state-wide assessment, habitat mapping, information synthesis and information dissemination through partnerships and co-operating agreements.

Analysis of the initial spatial data taken at the monitoring sites has already led to significant findings on the natural and anthropogenic factors responsible for spatial and temporal variation observed on Hawaiian coral reefs. Some highlights of the findings to date are as follows:

- Exposure (wave energy) was shown to be a significant factor in determining the structure of Hawaiian benthic and fish communities.
- Bottom relief (rugosity) is a significant factor in determining fish habitat quality, with a significant relationship between rugosity and fish biomass.
- All three monitoring sites in Kaneohe Bay, Oahu show rapid decline of coral cover and increasing algae cover.
- Average coverage for all CRAMP sites is approximately 23%. All transects are positioned on hard substratum. The sites were selected over a representative cross section of Hawaiian coastal environments, so this is probably a reasonable estimate for coral cover on hard substratum over the entire main Hawaiian Islands in the depth range sampled. Published literature values generally show coverage estimates higher (mean of the previously published values is approximately 35-40% cover). Previous studies often targeted high coral coverage areas rather than selecting a good cross section of reefs throughout the state.
- The reefs of Hawaii are best described as *"Porites reefs,"* being overwhelmingly dominated by massive and encrusting *Porites lobata* and branched *Porites compressa. Montipora capitata (=Montipora verrucosa)* and *Montipora patula (=Montipora verrilli)* also account for a significant amount of the coverage. *Pocillopora* meandrina is common in shallow turbulent environments.
- A latitudinal gradient in the coral community composition is not evident in these data. Coral cover appears to be controlled primarily by local variation in dominant environmental factors such as wave energy, bathymetry, watershed influences, substrate type, etc.

- Coastal sites with high wave exposure (e.g., Pupukea, Hoai Bay) have the lowest cover while bays and wave-protected coastal areas (e.g., south Molokai) have the highest coral cover.
- The most significant anomaly in coral coverage and reef conditions occurs off south Molokai. Coral cover along this coast is extremely high. The two sites with highest coral cover in the state (Palaau and Kamalo) are located here. A large zone of damaged reef occurs in the middle portion of the south Molokai coastline, between these two high-cover survey sites. Within this damaged zone is another survey site (Kamiloloa), which has the lowest coral coverage in the state.
- Areas protected from fishing have distinct assemblages and had higher biomass compared to areas where all fishing was permitted.
- The marine protected areas that were fully protected from fishing showed a much higher fish biomass than partially protected or open access sites. However, degree of protection did not show a relationship with coral reef community structure, probably because corals are protected and are not being harvested anywhere in the state.
- Surgeonfishes were the dominant fish family observed on transects, and herbivores accounted for over 70% of the total reef fish biomass over all locations.
- Fish assemblages in Kaneohe Bay, Oahu were very distinct and differed greatly from all other fish assemblages around the state.
- Initial assessment suggests that Hawaiian coral reefs are in better condition than in many other geographic locations. However, many of our reefs are presently undergoing degradation. The remainder may be dangerously close to the rapid decline that has been documented at other regions, such as the Florida reef tract.

Recommendations Related to this Workshop

1. A number of carefully chosen "Alpha Sites" must be monitored with high statistical power using contemporary digital image technology for benthic analysis. Standardized fish transects to quantify species abundance, size and biomass for the fish community. Physical parameters such as temperature and wave energy must be documented. A well-designed database is an integral part of such a program.

2. There must be a long-term commitment to any such monitoring and data base effort on the part of the funding organization. There is no point in starting a long-term program without such support.

3. General qualitative observations from trained local observers or one time only quantitative assessments are a valuable source of supplemental spatial information, but only in reference to the "Alpha Site" measurements. Aside from major environmental disasters, detection of trends in coral reef condition can only be established by proper monitoring techniques.

Monitoring of Corals, Bleaching and Protected Areas on the Great Barrier Reef

Jamie Oliver[1]
Ray Berkelmans[2]

Introduction

Monitoring is an essential tool for environmental managers and researchers. The increasing incidence of and interest in coral bleaching on reefs worldwide has highlighted the importance of effective, targeted monitoring programs. However very little dedicated monitoring for coral bleaching has occurred around the world, and recent estimates of the extent of coral bleaching world wide have been based primarily on anecdotal reports and unstructured visual assessment. Despite a long history of scientific monitoring and assessment, bleaching observations on the Great Barrier Reef (GBR) have generally been added on to existing monitoring programs. This has reduced the utility and power of these observations as tools to document and understand the bleaching phenomenon. In this discussion paper we will review key issues to be considered in designing monitoring programs in an ideal world. We then examine how various constraints and necessary compromises have limited the level to which bleaching has been monitored on the GBR, and describe other recent initiatives which have been very successful. Finally we briefly consider how a monitoring program might be developed to document bleaching on a global basis, and what issues should be considered in monitoring the effectiveness in mitigating the impact of bleaching of marine protected areas.

Design issues for monitoring on coral reefs

The main message of this section is that all monitoring programs must be explicitly linked to one or more issues and specific questions. There can be no single monitoring program for a coral reef ecosystem. Rather, a suite of targeted programs with specific management objectives is more efficient and effective than any omnibus program that attempts to answer all relevant management questions at the same time.

One definition of environmental "monitoring" is simply the collection of repeated observations on an environmental variable. However a more targeted definition in which the purpose for which the data collection is being undertaken is more helpful. The World Book dictionary, for instance, defines the verb monitor as "to check in order to control something." This definition clearly emphasizes one of the primary but sometimes forgotten purposes of environmental monitoring: to provide information on a management issue which may require management action. If people were not using the environment then there would be no need for environmental managers and environmental monitoring. Thus a good monitoring program is one which addresses a specific management issue in such a way that it provides information which enables timely and effective management intervention to alleviate potential (previously anticipated) problems.
On the Great Barrier Reef, the variety of monitoring programs can be divided, for convenience into 3 different categories: Site Specific Monitoring; Issue Specific Monitoring and Long-term Background Monitoring. Each type of monitoring requires somewhat different kinds of monitoring, although all require the majority of steps outlined above. Site specific monitoring examines a particular phenomenon at a specific location, and seeks to determine if this has led to changes in the characteristics of this site. Impact monitoring construction activities on coral reefs is a good example. Issue specific monitoring addresses the effects

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of a particular phenomenon that can occur widely in space and time. Crown-of-thorns starfish (COTS) and coral bleaching are good examples. These are issues which require monitoring over large space and time scales, but of only a small number of variables. Finally background monitoring addresses a general need to "keep and eye" on the state or health of the system in response to somewhat unspecified fears of anthropogenic impacts. As a result of this lack of specificity in the anticipated affects, these monitoring programs often attempt to measure several key variables which will act as indicators for the status of the whole system. They also tend to choose generalized spatial and temporal sampling regimes which will hopeful detect any anomalous behaviour in the system. These programs generally become more effective if they are allowed to continue for several years and decades and if they do not succumb to the temptation to switch variables and sites in order to suddenly address a pressing, temporary issue. On the other hand they also run the risk of never proving to be useful (since none of the things monitored ever went awry) and thus wasting precious time and resources.

Good design is essential for any monitoring program, yet it is often neglected in favor of getting into the field and collecting data on the first thing that seems sensible at the time. This frequently leads to a situation where the data are inaccurate, inconsistent and taken at spatial and temporal scales which are not relevant to the specific (but unspecified) problem at hand. The following steps provide a framework for the design and a development of a robust monitoring program which will provide accurate and relevant information to managers. A more detailed analysis can be found in Oliver (1999).

1. Identify Question(s)
2. Choose Scale
3. Choose Variables
4. Select Tools
5. Design Experimental/Sampling program
6. Collect Data
7. Analyze data
8. Act on results
9. Review

Of these, step 1 is by far the most critical for success, yet it is the one most frequently ignored, or addressed only by inference from statements made in the introduction of methods section of a report. Scale is also very important, especially in relation to issue specific monitoring. Most of the tools used by current monitoring programs are inappropriate for examining the global or regional distribution and intensity of coral bleaching.

Monitoring Programs on the GBR and the Documentation of Bleaching Patterns

Large-scale monitoring, aimed at providing a synoptic view of the status of the GBR, arose in the 1980's as a result of concern about the destructive effects of the crown-of-thorns starfish. Manta tow surveys in the 1970's were used to count COTS and feeding scars, but addition information was also collected on coral cover, and visually dominant organisms.

Long-term, government funded monitoring began at the Australian Institute of Marine Science (AIMS) in 1985 with the creation of a dedicated program to survey more than 100 reefs over several years. Reefs were selected on the basis of previous information on COTS outbreaks, and with an eye to making the sample representative of the whole GBR. The manta tow method was modified to create more precise estimates of COTS and to reduce the number of variables recorded to just those which could be mentally accumulated during the tow. In 1992, ongoing government funding was secured to continue and expand monitoring of the status of coral, fish and COTS. Video monitoring along a line transect, and visual census along a belt transect were used to monitor benthos and fish respectively. In order to maximize the utility of the existing monitoring data, benthic and fish monitoring sites were selected from among the sites already being monitored for COTS and from previously established fish census sites. This arrangement was a compromise between the desire to continue pre-existing time series data and the need to structure the sampling program to address the new objectives of documenting reef status over the whole GBR for the two major groups of reef biota (corals and fish).

A major stated purpose of the new Long-term Monitoring Program (LTMP) at AIMS, was to provide information to the Great Barrier Reef Marine Park Authority (GBRMPA), the management agency responsible for the marine park which encompasses virtually all of the Great Barrier Reef. Although GBRMPA played a significant role in reviewing and contributing to the design of the monitoring program (in particular the sampling design), it was not possible to directly address all the important management issues facing the Authority (Table 1). As can be seen from the distribution of monitoring sites in Fig. 1, the current LTMP is reasonably effective at addressing the issue of large-scale long-term trends and back-ground variability, although even here the original focus on COTS and reef fish on the mid to outer shelf, led to an underrepresentation of inshore reefs, which are the most vulnerable to land based impacts.

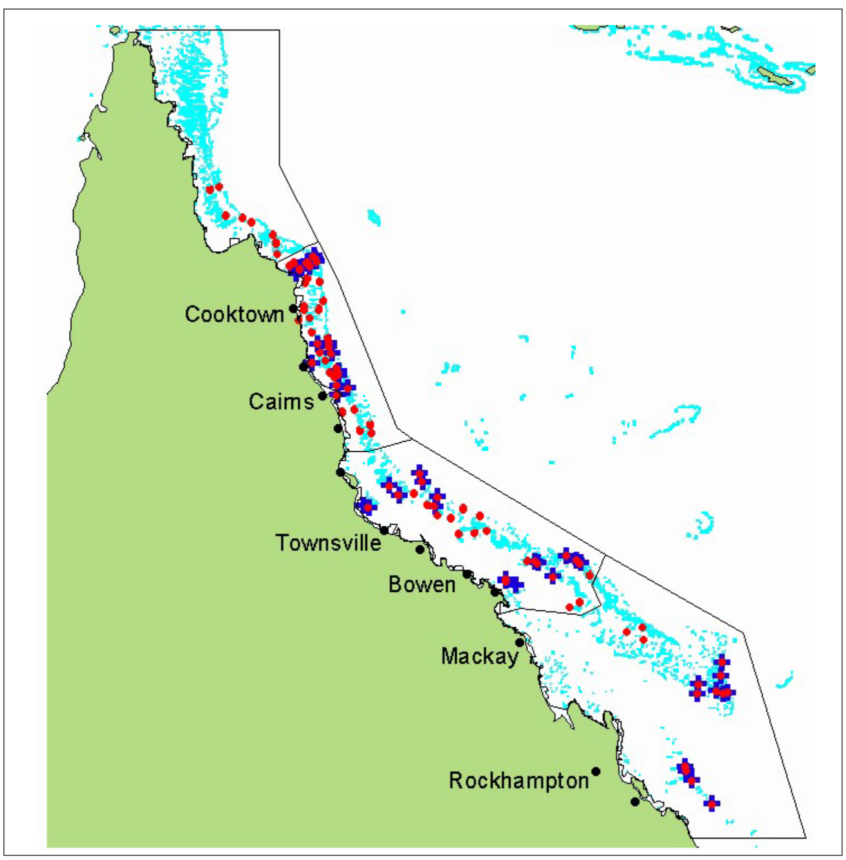

Fig. 1. Locations of monitoring stations for the AIMS LTMP

Table 1. Match between AIMS LTMP and priority GBRMPA issues (1996).

GBRMPA Management Issue[1]	[2]Priority	[2]Degree addressed by LTMP
Terrestrial run-off from land-based activities	1	4
Effects of Line Fishing	2	5
Large-scale changes in biota	3	2
Natural Variability	4	1
Global Climate Change	5	3

[1]These issues relate to the coral reef habitats within the Marine Park. In recent years, a major priority has been impacts of trawling on soft sediment communities in non-reefal areas. 2Highest=1; Lowest =5

This synopsis of the evolution and current scope of the principle coral reef monitoring program on the GBR (AIMS LTMP) is relevant since it demonstrates how the legacy of previous programs and issues and the desire for data continuity can influence the design of new programs. On the Great Barrier Reef, initial interest in COTS damage, prior fish population biology research and a traditional ecologically based focus on trends and variability have molded the AIMS LTMP program. However current research and management issues center around other issues. The lesson for others here is that it may be optimistic to assume that an effective monitoring program for coral bleaching can be added to pre-existing scientific monitoring programs.

Despite the size and sophistication of the AIMS LTMP, the issue of coral bleaching could not be fully investigated as part of this program. Although the scale of the program is appropriate, the timing of surveys, and the need to maintain a consistent temporal sampling program to meet its main objectives, means that only a small portion of the GBR is likely to be surveyed during the period when bleaching may be occurring (usually over a 3-4 month period). Consequently, the documentation of bleaching and associated temperature events on the GBR has been largely carried out as a separate exercise by GBRMPA and AIMS. Early records of bleaching on the GBR were accumulated via verbal reports and interviews of scientists and tourist operators. These were generally initiated by GBRMPA once preliminary reports of bleaching had been received. However, the AIMS LTMP, other research projects and other monitoring projects commissioned by GBRMPA to address other impacts have been extremely useful in providing information which, during some events has represented the bulk of our records. In later years, dedicated surveys of particular sites known to be affected, were carried out by GBRMPA and AIMS scientists, and dedicated reply paid questionnaires were sent to a range of reef users. It was only during the 1998 bleaching event, however, that any specific attempt to document the extent and severity of bleaching on the GBR was carried out (Berkelmans & Oliver 1999). This was made possible through the establishment of a GBRMPA budget line for unspecified disturbance monitoring (in a sense a contingency budget). It also benefited from the realization, over past bleaching events, that severe bleaching could be observed from the air.

During the 1998 episode, aerial surveys were conducted during periods of low tide. A total of 654 reefs (23% of the GBR) were surveyed during 10 days of observation over a period of only a month. Reefs were visually classified into one of 5 categories (extreme [>60% bleached]; very high [30-60%]; high [10-30%]; moderate [1-10%]; low or none [<1%]). The accuracy and precision of these visual estimates were controlled as follows. Precision was maximized by flying at similar times of day, tide, and visibility, and by using a single observer for almost all observations. Accuracy of the visual estimates was calibrated by a series of dedicated video surveys and visual assessments along replicate line transects at a representative sub-sample of the reefs surveyed from the air. This calibration exercise demonstrated a good correlation between the different techniques, and a tendency to underestimate the true level of bleaching. Overall, the surveys and analysis cost about US$10,000. This was considered to be a extremely cost effective way of obtaining synoptic information over the whole Great Barrier Reef at a high sampling rate (>20%) By comparison, the AIMS LTMP has costs which are over an order of magnitude higher.

It can be seen from Fig. 2 that the earliest records did not include information on where reefs were not bleached. It is also clear that the level of sampling effort was not uniform over all episodes, and has increased substantially over time. Consequently the utility of this observation series in describing temporal patterns is limited. However, the level of coverage obtained in 1998 is sufficient to conclude that there were significant inshore-offshore and north-south differences in bleaching which are consistent with the indications provided in the less comprehensive results of the previous episodes. These spatial differences were highly correlated to patterns of SST for the period, obtained from NOAA high resolution LAC satellite imagery.

Table 2 summarizes our knowledge of the severity of and periodicity of bleaching on the GBR. The results (paying heed to the lack of consistent sampling effort), would appear to suggest that bleaching has been occurring at intervals of 2-5 years over the last two decades. There is no evidence at this time that either the severity or the frequency of bleaching is increasing with time.

Table 2. Frequency and intensity of bleaching events on the GBR

Year	Interval	Severity
1980	-	Low
1982	2	High
1987	5	Medium
1992	5	Low
1994	2	Low
1998	4	High
2002?	4 or more	

An important point to be drawn from the above results is that the monitoring programs which were most effective in determining the overall impact of bleaching on the GBR were generally large in scale, low in resolution, rapid in response, and backed up with more detailed observations within a structured and representative subset.

An interesting preliminary result from analysis of the relationship between bleaching status and zoning (Table 3) is that there is a significantly smaller proportion of bleached reefs in protected areas compared to unprotected areas. The cause of this pattern is uncertain. One possible explanation is that there are more protected areas in offshore areas, and in the far northern section where bleaching was generally less severe.

Another way of dealing with the need to cover large spatial scales at relatively low cost is to take advantage of volunteer networks or to create special volunteer organizations to gather monitoring data. ReefCheck is an excellent example of this on a global scale. On the Great Barrier Reef, GBRMPA has coordinated a volunteer monitoring program over the last 3-4 years called Eye on the Reef. This program utilizes diving staff on tourist vessels visiting the reef to carry out routine observations. We have had mixed success with this approach. Whilst it is potentially an invaluable means of acquiring relevant data, we have found that it requires the services of a half time coordinator and a contract database programmer in order to set it up to work effectively in just one section of the marine park. Problems that have required resolution and ongoing attention include: variable commitment from the participants which creates variability in the data quality; difficulty in finding variables which were relevant to the Authority's monitoring interest and which could be reliably measured by non-scientific staff in the time available to them; and gaps in data sets caused by lack of time for monitoring when other job priorities take precedence over monitoring. However, this volunteer network has been invaluable in providing early warning and initial estimates of bleaching at a variety of sites.

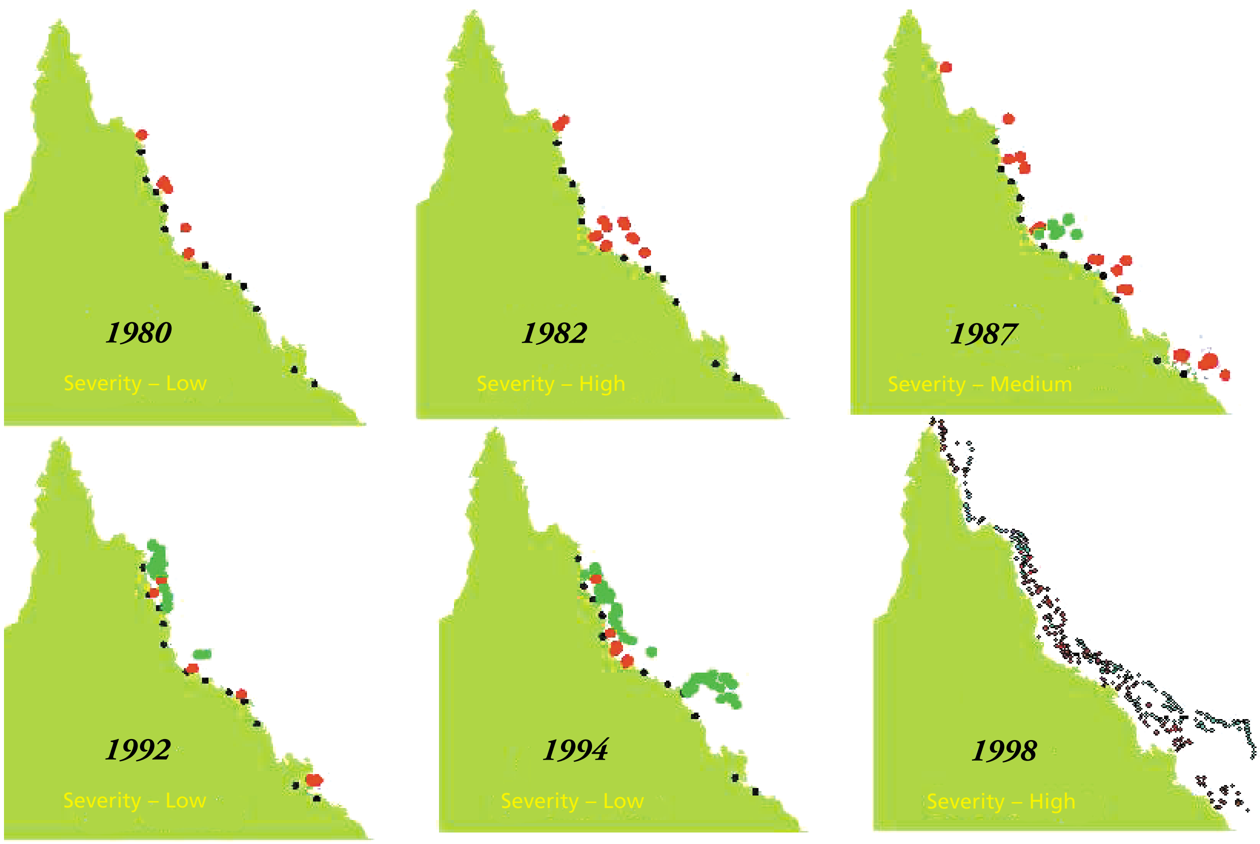

Fig. 2. Bleaching occurrences on the GBR over the last 2 decades.

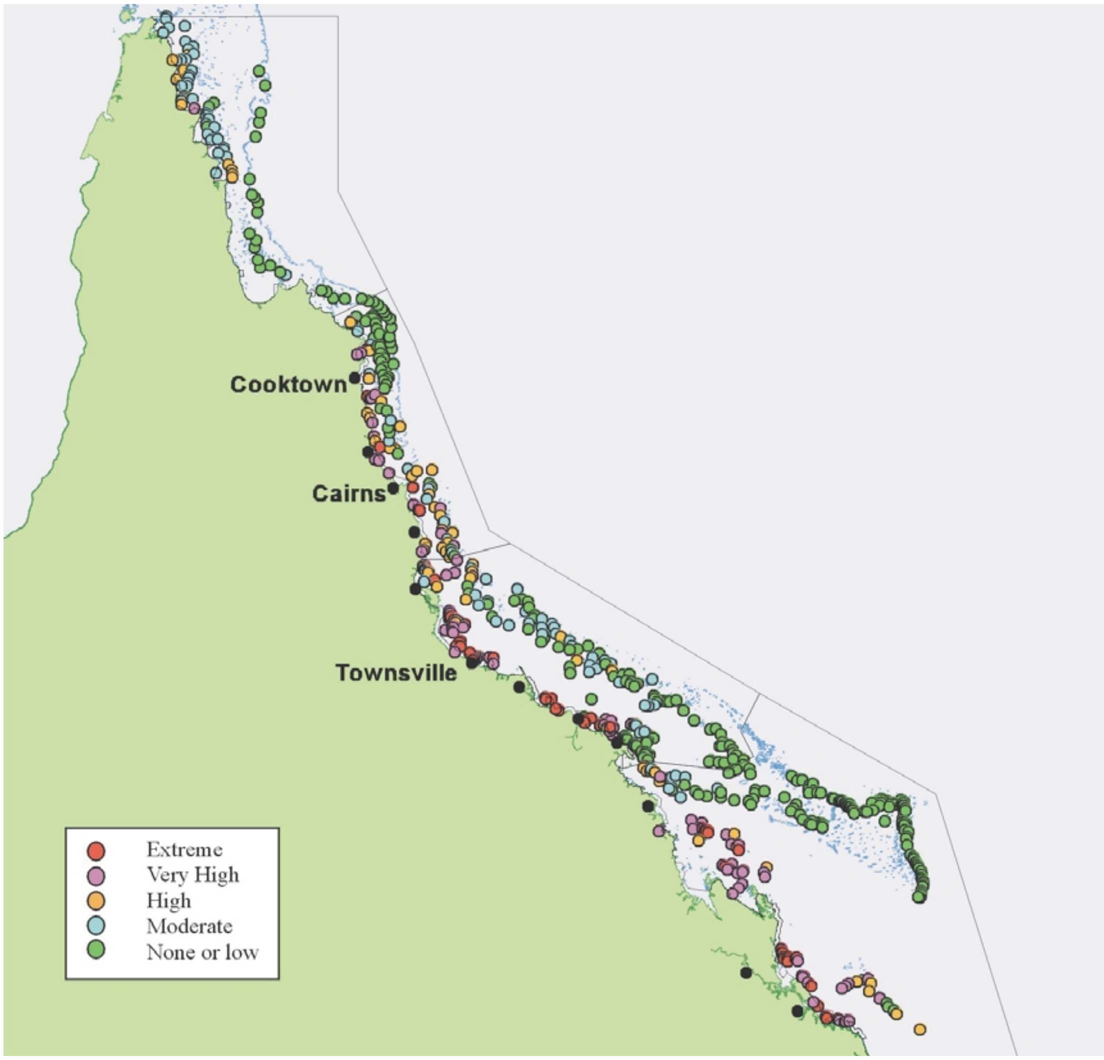

Fig. 2b. Distribution of bleaching on the GBR in 1998

Table 3. Distribution of bleaching in protected and unprotected areas.

		Bleaching Level					
Status		Extreme	Very High	High	Moderate	None	Total
Protected	Count	9	16	25	20	72	142
	%	6.3	11.3	17.6	14.1	50.7	100.0
Unprotected	Count	54	76	45	77	194	446
	%	12.1	17.0	10.1	17.3	43.5	100.0

Monitoring activities directed at a better understanding of coral bleaching, have also included the development of a major sea temperature monitoring program. Through a combination of weather stations operated by AIMS, and a dedicated sea temperature monitoring program using underwater loggers initiated by GBRMPA, water temperatures have been recorded at half hourly intervals at over 40 sites along most of the length and breadth of the GBR for 2-5 years. The logger data are downloaded in to a central database at GBRMPA and summary data (weekly or monthly averages) are freely available on the web (www.gbrmpa.gov.au/seatemp/index.html). Since the loggers are left in the field for between 6-12 months, the data on the database can be up to a year old. The AIMS weather stations form an important compliment to the logger data since they provide real-time (half hourly) data which is available online within AIMS and GBRMPA. An important feature of the logger system is redundancy. Logger failure or loss is a common occurrence, which can leave significant gaps in a time series. At most sites four loggers are deployed: two on the reef flat and two on the reef slope. A separate study (Berkelmans and Oliver, submitted) indicated that there is little or no difference between reading at a similar depth but separated by a few hundred meters, and no meaningful difference between daily mean temperatures even for loggers a different depths.

This temperature monitoring program has enabled researchers to clearly attribute seasonal temperature anomalies as the cause of bleaching events, and to estimate bleaching thresholds for corals at different latitudes (Jones *et al* 1997; Hoegh-Guldberg 1999). The data also demonstrate that these temperature extremes occur over a wide area, but have clear regional differences. For instance, the anomalous temperatures of 1998 are much more evident at Orpheus Island and Middle Reef (nearshore sites) than offshore at Kelso Reef (Fig. 3), and this matches the survey results which show much higher bleaching and subsequent mortality at Orpheus Island. Although not essential in a program aimed simply at documenting the severity and extent of coral bleaching, sea temperature data are critical in demonstrating climate variability and bleaching. This enables differentiating between temperature induced bleaching and that caused by other factors, such as low salinity, which are reflected in the bleaching patterns. For instance, the results for Middle Reef (Fig. 3), show the sudden influx of cooler water during a major flood event in Townsville. However the onset of bleaching did not occur until some time after this, when temperatures had climbed back to very high levels.

Some Considerations for the Design of a Global Monitoring Program for Coral Bleaching

There appear to be several potential objectives and associated questions that a monitoring program for coral bleaching should address:

1. To document spatial and temporal distribution of coral bleaching and recovery.
2. To document adverse flow-on effects on the ecological function of reefs.
3. To determine how any adverse impacts on coral reefs are affecting human communities that depend on them.
4. To determine if any human interventions on coral reefs (such as MPA establishment) are able to reduce the susceptibility and/or ameliorate the subsequent impacts on both the reef and on associated human communities.

Each of these objectives is both relevant and important (there are probably many more), and each requires somewhat different activities and expertise. Any one of these would required enormous resources of funds, manpower, and access to expertise which exceeds the capacity of any existing organization. While objective 4 is closest to the focus of this workshop, it also is dependent on information from the other items (particularly objective 1).

One of the main reasons that coral bleaching has attracted so much attention and alarm is that it appears to be a global phenomenon, caused to some extent by global climate change. Thus the issue of scale for

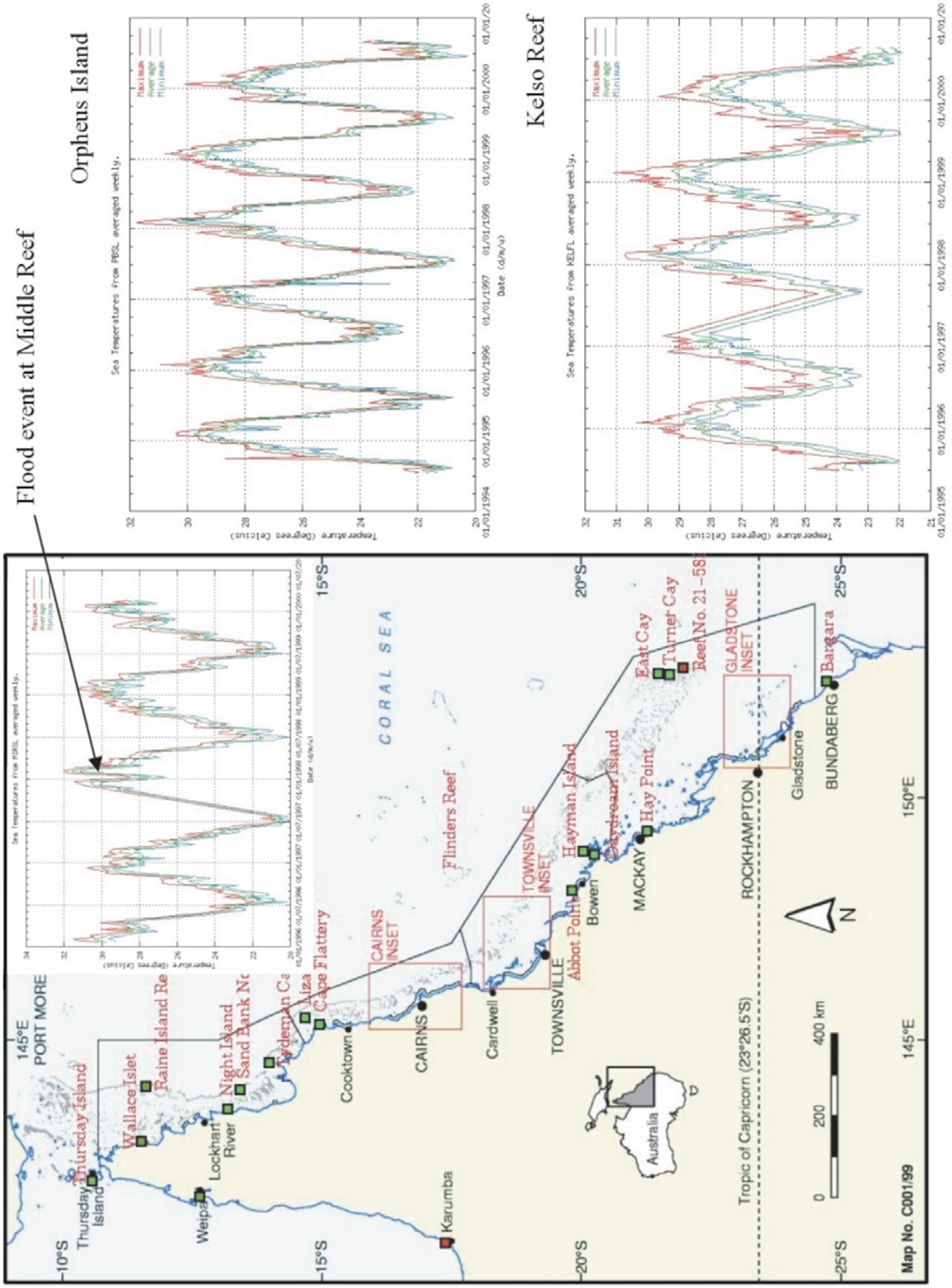

Fig. 3. Temperature monitoring stations on the GBR and sample online outputs.

monitoring is problematic. If we wish to determine the extent to which bleaching threatens reefs worldwide, then it is important to monitor a representative selection of sites worldwide. From the perspective of temporal scale, the relatively brief period during which bleaching is visually obvious at any one site also means that monitoring will have to commenced at short notice, with funding which has been pre-allocated or can be rapidly sourced. In addition, if objective 4 is to be addressed, then we must consider the likely timeframes over which effects of management interventions would operate, and the magnitude of the effect which we would anticipate. In this respect, it seems likely that the effect could be quite small and would take a long time to manifest itself.

The following considerations are relevant for the development of a monitoring program to address objectives 1 and 4.

1. The program should be capable of rapid initiation following the onset of bleaching.
2. It should be pre-designed with assistance from experts in monitoring and sampling strategies, so that there is minimal delay in initiation, and a low risk that design flaws would compromise the results.
3. It should incorporate planned comparisons between bleached and unbleached areas in both protected and unprotected sites.
4. It should concentrate on visual assessment methods which can cover large areas with only moderate precision (aerial surveys, manta tows, timed swims). This should be complimented by more detailed surveys at selected sites. Some consideration should be given to training and projects in order to address the issue of inter-observer variability, which is a significant problem with visual assessment techniques.
5. The program should incorporate detailed monitoring at representative sites in order to calibrate visual assessments.
6. Temperature, monitoring using inexpensive submersible data loggers, should be used at a selection of sites so that the role of temperature in inducing bleaching can be clarified, if needed, and so long term trends can be documented.
7. While a dedicated effort will be required during any bleaching event, monitoring of protected and unprotected areas will be required during non-bleaching years, and would serve as a focus for the development of national capacity in monitoring and assessment.
8. Any monitoring effort that is global in scope will require substantial coordination of activities and data. The establishment of a centralized database with online web access to the data from all participants should be considered.

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Coral Reef Bleaching and Monitoring in the Indian Ocean

David Obura (Compiler)[1]

Abstract

Coral reefs of the Indian Ocean were some of the most affected by the El Niño coral bleaching event of 1997-98, and apparently among the most degraded regions in the world. The GCRMN global report (Wilkinson 2000) summarizes the status of Indian Ocean reefs as follows: destroyed before 1998 – 13%; destroyed in 1998 – 46%; estimated critical in next 2-10 years – 12%; estimated loss in 10-30 years – 11%. This yields a total of 59% of all Indian Ocean reefs that are currently seriously degraded, with the prediction that this will rise to a total of 82% of all Indian Ocean reefs in the next 10-30 years. This paper summarizes the status of coral reefs in the Indian Ocean following the bleaching event of 1998, with updates, where available for early 2001. Following this, some of the bleaching patterns are summarized. This paper does not include the eastern Indian Ocean (west of the Andaman and Chagos Islands) nor the Arabian region and Red Sea. Historically, these areas have had a separate regionalization of scientific, cultural, and political interests. Collaboration with these regions is improving however, and should be supported through this initiative.

In the face of these dire predictions of coral reef degradation, action does need to be taken to safeguard the benefits Indian Ocean countries and their peoples derive from coral reefs, as well as to preserve the biodiversity and ecosystem functioning of coral reefs. How to achieve these goals is not clear, and there is a clear need to develop new strategies and options for management that incorporate bleaching issues. The extent of Marine Protected Areas, and of regional monitoring programs is summarized here to set the stage for developing new management and monitoring actions responsive to bleaching. The Indian Ocean does present numerous opportunities for collaboration and networking, from local project to inter-governmental agency levels, and a fast-growing awareness of and commitment to addressing the threat of coral bleaching.

The El-Nino in the Indian Ocean, 1998

The sea surface temperature anomaly map (Fig. 1) shows the position of the high in April 1998, having moved northwards from a position off Madagascar and Mozambique in February, and finishing in the Gulf of Aden in May. The warm pool of water was caused by high insolation when the sun is overhead (January–April in the Southern Hemisphere) causing doldrum conditions in the Inter-Tropical Convergence Zone (ITCZ). Heating is intensified during El Niño by abnormally calm and clear conditions. Northward progression of the sun from February to May caused the pool of warm water, which started off in Madagascar/southern Mozambique in February, to migrate northwards to Somalia by April/May.

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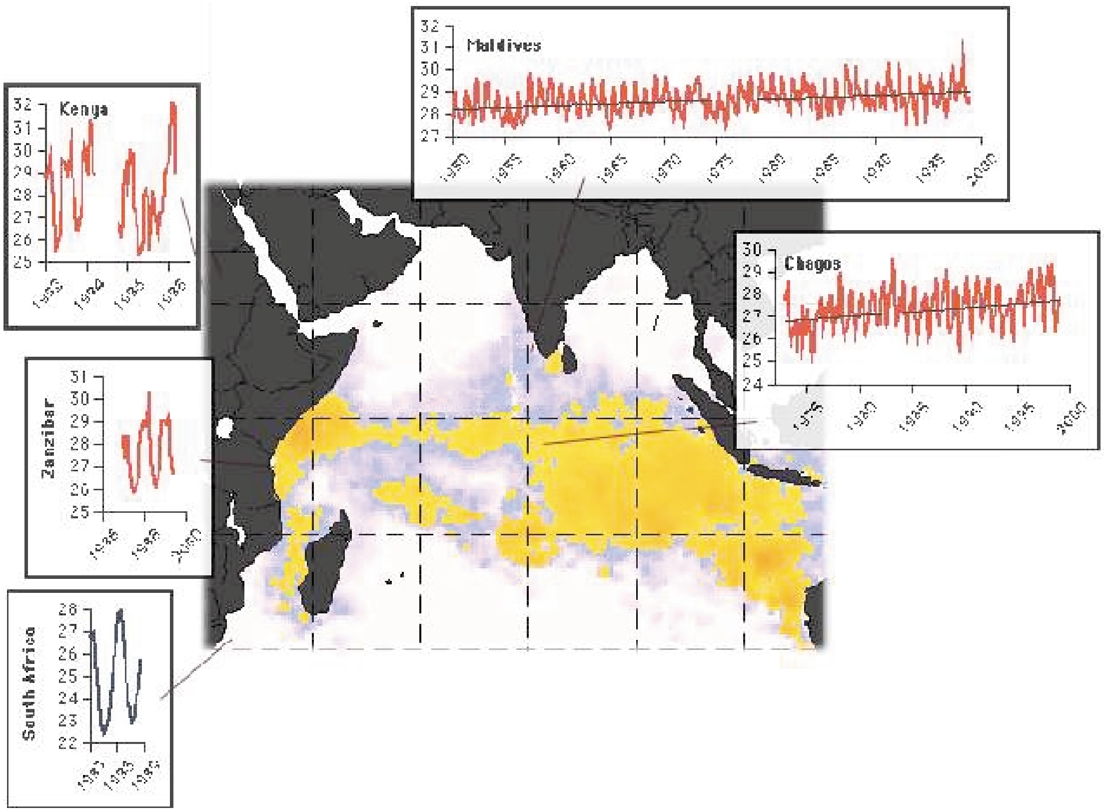
Fig. 1. Indian Ocean HotSpot map from April 1998 with available temperature records for Kenya, Zanzibar, South Africa, Maldives, and Chagos (Sources: Chagos—C. Shepphard; Maldives—S. Clarke, A. Edwards; Kenya—D. Obura, T. McClanahan; Zanzibar--C. Muhando; South Africa--M. Schleyer. Map: CHAMP website)



Long term records – the central Indian Ocean shows a distinct warming trend (Chagos, Maldives) over 3-5 decades, leading up to the highest recorded maximum during the El Niño Southern Oscillation in early 1998.

Local measurements – sea surface temperature measurements are now being taken by a number of different methods, including spot measurements using thermometers during field visits, automated measurement by in-situ temperature loggers, ship-based temperature measurements, and satellite remote sensing of sea surface temperature. With increasing variety of methods and number of locations monitored, standardization among methods will become more important, to account for differences in resolution in space and time, depth of measurements, daily variations, etc.

Status of Reefs – 1999-2000

The following country reports are excerpted from sub-regional and national summaries in the CORDIO 2000 report (Souter *et al.* 2000). Additional observations contributed by individuals are indicated where appropriate. In general terms, more southerly sites escaped bleaching through predominantly lower temperatures and greater incidence of storms. Equatorial areas suffered the highest levels of bleaching (Kenya, Seychelles), with high levels recorded at more northerly latitudes (Maldives, Arabian Gulf).

Table 1. Summary of reef status in the Indian Ocean, with respect to coral bleaching in 1998 and subsequently.

	Latitudinal range (°S)	1998 Bleaching	1998 Mortality	Recovery	2001 Status
East Africa					
South Africa	26 – 27	< 1%	none	–	No bleaching
Mozambique	12 – 26	10-50%	10-50%	patchy	Cyclone and flooding damage
Tanzania:	5 – 12	Approx. 50%	Approx. 50%	patchy	Low bleaching
Kenya:	2 – 5	50-80%	Approx. 50%	patchy	Low bleaching
Islands					
Comoros		10-50%	10%	some	–
Madagascar		yes	15%	?	Low bleaching
Mauritius		< 10%	negligible	–	
Mayotte		high	10-70%	variable	
Reunion		low	none	–	
Rodrigues		yes	yes	Moderate	Destructive
					fishing and runoff damage
Seychelles		high	high	patchy	Recovering
South Asia					
India		Variable – moderate to high	Variable – moderate to high	–	–
Maldives		95%	95%	Recruitment patchy/high	Recovering
Sri Lanka		High in shallows	High in shallows, low > 10m.	low	–

East Africa. East Africa, comprising Kenya, Tanzania, Mozambique, and South Africa, was greatly affected by coral bleaching and mortality as a result of the 1997-98 El Niño. Bleaching most probably started in East Africa in late February–early March, in the south, and finished in May in the north, following the movement of the sun and the Inter-Tropical Convergence Zone. At any single location, surface water temperatures were raised for about 2 months, with severe bleaching for 6-8 weeks progressing into mortality up to 4 months later. While many shallow reefs suffered mortality levels of > 50%, some exceeding 95%, there were significant areas with low coral mortality of less than 20%. Recovery of affected reefs to the beginning of 2000 has been slow, and principally through growth of surviving colonies as coral recruitment rates have been low.

South Africa. South Africa's reefs are generally deep (> 8m) and on offshore, high energy banks. Bleaching due to the El Niño was very low, at < 1%, and full recovery was reported. The depth and high wave energy of the reefs is likely to have protected them from higher impacts.

Mozambique. Mozambique's coral reefs are most highly developed in the north (from 17°S northwards), with isolated reef areas and coral communities on the southern coast from Bazaruto (21°S) to the South African border. Together with southern Tanzania, the northern Mozambican coast is likely to be the center of diversity of the East African reef fauna. Coral bleaching and mortality due to the El Niño was highly variable among sites surveyed, with most sites in the north registering 30-80% mortality of corals, and in the south, 0-20%. Coral cover following mortality is noticeably higher inside Marine Protected Areas than outside. Algal cover now dominates most reef areas, with no coral recruitment noted as an indicator of recovery. Baseline data on invertebrate and fish populations has been recorded in 1999 for monitoring of long term effects.

Tanzania. The entire Tanzanian coastline supports coral reefs, from 5 to 11°S. Coral bleaching and mortality were recorded the whole length of the coastline, though at varying levels. Reefs that suffered the highest mortality levels of about 80% included Mafia and Pemba Islands. The majority of reefs were recorded with mortality levels of about 50%, including islands south of Zanzibar town and in southern Tanzania. A number of reefs showed very low mortality, and even increases of coral cover over previous years. Most of these reefs were on the west coast of Zanzibar Island and the mainland around Dar es Salaam, where lower temperatures were recorded due to upwelling of deeper water. Many of these reefs were already highly degraded due to anthropogenic threats prior to the El Niño. Baseline data on invertebrate and fish populations has been recorded in 1999 for monitoring of long term effects. Increases in coral competitors that thrive on degraded reefs (Corallimorpharia) have been documented, which may significantly retard reef recovery. Monitoring of fisheries and tourism have shown the potential for losses in income following reef degradation, however these impacts are not yet being felt.

Kenya. The southern Kenya coast is fringed by a continuous 200 km fringing reef, while reefs on the northern coast are less developed due to cold-water influence from the Somali current system. Coral cover decreased from pre-bleaching levels of 30-50% to post-bleaching levels of 5-10% on most reefs, representing losses of 60-90%. Shallow reefs on the southern coast were most affected, with less impact at depth and northwards, though individual reefs throughout the coast were found with close to 100% mortality. Recovery of some lagoon patch reefs in the south has been noted, primarily by regrowth of surviving colonies, and partially by recruitment of some opportunistic coral species (e.g., *Pocillopora damicornis*). On the whole, however, coral recruitment has been low. Monitoring of zooxanthellae and chlorophyll concentrations in 5 coral species has been continued since the El Niño, to provide baseline data for future events. Studies of components of the benthic community are investigating the responses of macroalgae, microalgae, and bioeroder communities following the coral mortality. Fisheries catch monitoring is being conducted by a number of groups, however no response to the El Niño has yet been noted.

Indian Ocean Islands

Comoros. Coral reefs surveyed in Comoros exhibited only around 10% coral mortality from the bleaching. Live coral cover remained high (36-40%) and dead coral comprised approximately 47% of the substrate. The reef supports both fisheries and tourism. The fisheries remains a small supplier of food to the country but provides employment for a large proportion of the population. In Comoros, reef-based tourism is an important component of a rapidly expanding tourism industry.

Madagascar. The increased sea temperatures recorded in 1998 did not particularly affect the coral reefs of Madagascar. At the survey site, live coral cover was over 40% and only 15% of the 55% dead coral cover was thought to be due to coral bleaching. Overfishing is a critical issue affecting these reefs. Reef fisheries contribute 43% of Madagascar's total fish catch and are an important source of food and also foreign earnings.

Mauritius. The reefs of Mauritius were not adversely affected by the bleaching event in 1998. The reefs are heavily utilized and are facing other threats at present. They support an extensive fishing industry with the lagoonal catch increasing. Most tourists who visit the island will be involved at some stage of the vacation with reef-related activities.

Mayotte. Most coral communities in Mayotte suffered from the bleaching. Live coral cover on the reef flats was low (4-6%) while on the deeper reef slopes it ranged between 20-28%. As with corals in the lagoons of reefs in the southern Seychelles, corals in the lagoon of Mayotte were less affected than those on adjoining reef flats and appeared to be adapted to fluctuations in water temperature.

Reunion, France. Reunion was not severely affected by the bleaching and those colonies that did bleach are now showing signs of recovery. Live coral cover at the survey sites is reported to be in the region of 30-40%.

Rodrigues. Rodrigues was surveyed comprehensively in July 2000 for the first time since the bleaching event in 1998 (Turner, Chapman, Hardman and West, pers. comm.). Coral mortality from the 1998 bleaching was significant and high: it was visible through the loss of large coral patches described and recognized from surveys in 1978, and by an increase in cover of lagoon vegetation. No new bleaching was observed, but impacts from destructive fishing and runoff were significant.

Seychelles. The coral reefs of Seychelles were possibly the reefs most affected by the 1998 bleaching event. Live coral cover of the Seychelles granitic islands have been reduced to less than 10% on most reefs and signs of recovery are slight with low recruitment and 35% of the sties showing no recruitment at all. This has led to the breakdown of the reef infrastructure and is likely to result in gradual erosion of the beaches. The lagoonal reefs in the outer islands appeared to have adapted to fluctuations in temperatures and faired relatively well, while the branching colonies of the shallow reefs were severely affected (Teleki and Spencer 2000). Recovery from the bleaching in Aldabra is underway as many coral suffered only partial rather than total mortality. At all sites affected by the coral bleaching, the gradual breakdown of the reef is being seen. This will have a negative effect on the invertebrates and fish that utilize the reef structure for shelter.

South Asia

The reefs of South Asia, including Maldives, Sri Lanka, and India were severely affected by the bleaching event of 1998, with subsequent mortality ranging between 50-100%. Surveys of these reefs conducted during 1999 and the beginning of 2000 recorded some coral recruitment, but many areas still show no signs of recovery.

India. The reefs of the Gulf of Mannar were severely affected by mortality of coral during 1998. Post bleaching surveys on the coral reefs of the 21 islands in the Gulf show the mean cover of coral as approximately 26%. However, there is considerable variation between reefs with the cover of live coral ranging between 0 and 74%. In addition to reef-building corals, sea anemones and octocorals also bleached as a result of the increase sea temperatures that prevailed during 1998. Subsequently, a decrease in biodiversity of these reefs has been reported. Furthermore, extensive beach erosion on some islands was reported.

Initial assessments of recovery in Lakshadweep Islands during 1999 indicated the cover of live coral has increased to 15-20% compared with 5-10% immediately after the bleaching event. Infrastructure and capacity needed for continuation of the work are being created. Early reports from the Andaman and Nicobar Islands indicated 80% of all corals bleached. However, the extent of post bleaching mortality has not been established.

Maldives. Results of monitoring of the reef tops conducted during 1999 show that the cover of live coral has not increased since the post bleaching surveys conducted in 1998 and remains at approximately 2%. At present, the cover of live coral is 20 times lower than that recorded before the bleaching event. However, recolonization of fast growing branching corals has been recorded, indicating that reef recovery processes are underway. Furthermore, on some reefs coralline algae are abundant providing potential areas for coral recruitment. Nevertheless, despite these reasons for hope, it is clear that the reefs of Maldives were seriously affected by bleaching and subsequent mortality of coral and will require many years to recover.

In addition to biophysical monitoring of the reefs, studies were conducted to determine the spatial and temporal patterns of coral recruitment in Maldives. Initial results suggest that there is potential for the degraded reefs of Maldives to recover through the influx of coral planulae from surviving colonies elsewhere. Also, the degree of erosion and changes in the topographic complexity for these reefs are being assessed following the extensive coral mortality in Maldives.

Sri Lanka. Most shallow coral reef habitats in Sri Lanka were severely damaged as a result of coral bleaching in 1998. Surveys conducted between June 1998 and January 2000 revealed that many of the dominant forms of reef building corals in the shallow coral habitats have been destroyed. Invasive organisms such as tunicates, corallimorpharians and algae now dominate the dead coral reefs. Furthermore, the dead coral patches were rapidly inundated by sediment thus preventing recolonization of coral larvae. Also, in every area surveyed thus far except Trincomalee in the northeast, the hydrocoral, *Millepora*, which was once common, appears to be completely absent. However, despite the destruction of corals in shallow water (< 8m), corals growing in deeper waters (> 10m) have recovered from bleaching almost completely, providing a source for new recruits and reef recovery.

Recovery of bleached corals in shallow reef habitats has been extremely low and has been hindered by further damage to the reef structures by uncontrolled and destructive human activities. Even the marine protected areas in Sri Lanka are largely unmanaged and increasing human activities within these protected areas continue to degrade their condition. Considering the present condition of the reefs and the inevitability of future anthropogenic impacts, the prospects for reef recovery are poor.

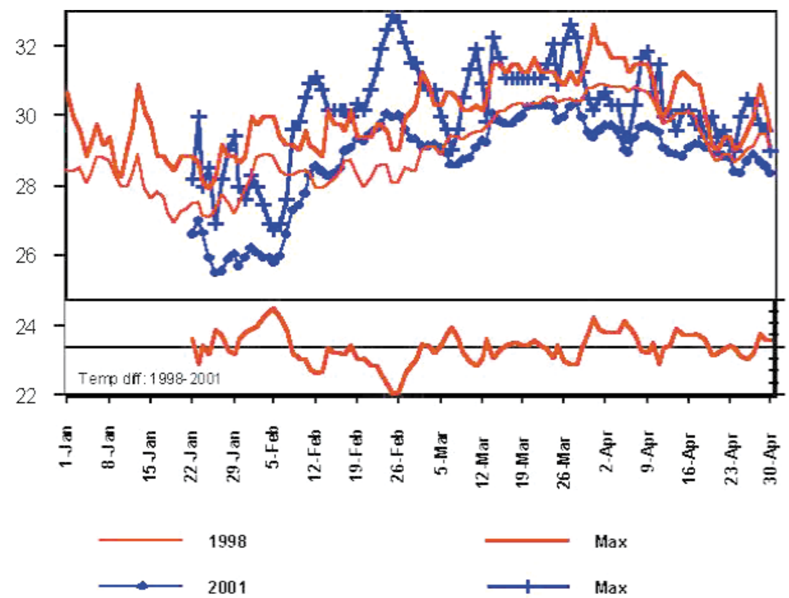
The impact on fishes by the loss of live hard corals is clearly visible in the decrease abundance of several species of fish that depend on live corals for food (e.g., chaetodonts). However, it is less obvious in fish populations in deeper water that are less dependent on live corals for their survival. Nevertheless, it is expected that the reduction in cover of live hard coral will directly affect the fishery potential of reefs through habitat degradation and loss thus, having an adverse impact on the income of coastal communities.

Status of Reefs – 2001

Sea Surface Temperature, 2001

In early 2001, the renewed coral bleaching was predicted on the basis of potential El Niño predictions and slightly elevated sea surface temperatures.

Fig. 2. Temperature logger records from Mombasa Marine Park for January–April 1998 and 2001. Mean and maximum daily records shown, of 48 measurements per 24 hour period. The lower line shows the excess of 1998 temperatures over 2001, showing a maximum difference of ±4 °C, between the dotted horizontal lines and the 1 °C ticks on the right vertical axis.



Temperature records from Kenya are shown in Fig. 2, contrasting mean and maximum daily temperatures for the 1998 bleaching event from January to April against measurements for 2001. Strong northeast monsoon winds in January/February 2001 caused greater than normal water mixing and lower sea surface temperatures at the beginning of February before calm conditions prevailed. The water temperature increased sharply in mid-February and subsequently matched 1998 temperatures until early April. The sharp drop in temperatures in early February may have been a significant factor in preventing widespread bleaching, though minor bleaching was reported from various parts of the region (see next section).

Country Updates

As in the previous section update reports from countries are attributed to individuals who communicated the information in March/April 2001.

Madagascar. Bleaching was reported at Tulear in early 2001, though it was not as extensive or extreme as in 1998. Low mortality was reported (A. Cooke).

Mozambique. The annual monitoring program in Mozambique, completed in January 2001, recorded reasonable reef recovery, from both coral regrowth and recruitment. The only exception was in the Quirimbass

Archipelago in northern Mozambique, which prior to bleaching in 1998 was the most extensive and diverse coral reef system in Mozambique. Mozambican reefs were heavily impacted by other threats in 2000 and 2001, including cyclone and flooding damage. Corals in the lagoon at Xai Xai in southern Mozambique suffered 40% mortality (H. Motta).

Tanzania. Long term monitoring of reefs in the Mafia Marine Park revealed reasonable recovery, from both coral regrowth and recruitment (J. Rubens, S. Mohammed). Nevertheless, bleaching was reported from Mafia and parts of southern Tanzania (J. Daffa), but at lower levels and with less mortality than in 1998.

Kenya. Recovery of coral reefs has been patchy, with significant regrowth and recruitment in many locations. Coral community structure has switched to minor genera such as *Platygyra, Coscinarea,* and *Pavona.* Massive species of *Porites* are still dominant in many areas, while *Acropora*, which was previously abundant is now rare and showing low levels of recruitment. Recruitment is dominated by *Pocillopora* species and patchy, between 0-20 m^{-2} on good reefs. On reefs in northern Kenya, coral species richness fell to 25% of pre-bleaching levels in 1999, but has risen to 50% in early 2001 (D. Obura). Bleaching in 2001 has been minor, first seen in early April in the Kiunga area and subsequently in Mombasa (J. Church, J. Tamelander). The majority of *Pocillopora* colonies, both adult and recruits, were bleached or pale, and partial bleaching and paling has been reported for *Galaxea* and *Acropora.*

Fish populations on the whole have been unaffected by the El Niño related coral mortality in 1998 (T. McClanahan). An exception is butterflyfish species richness, where the response depended on the management status of the reef. Butterflyfish species richness has declined consistently in protected reefs since 1998, remained unchanged in unprotected reefs, and the long term rise in newly protected reefs remained unaffected.

Aldabra. The second survey expedition to Aldabra was conducted in early 2001, following up on initial assessment in 2000 (K. Teleki, T. Spencer). Recovery in 2001 has been reasonable, witih coral cover varying between 20 and 30% at most sites (D. Souter). Changes in coral community structure were observed, with rare genera becoming dominant. Coral recruitment was patchy, varying from 0-20 m^{-2}, and higher in shallow water. Dominated by *Pocillopora* and *Pavona*, then *Psammocora*, Favids and occasional *Acropora.* Species diversity in the fish community has increased, due to greater numbers of small invertebrate feeding species, such as butterflyfish, gobies, etc.

Summary. Minor bleaching occurred in several parts of the Indian Ocean in 2001, however full El Niño conditions did not occur so bleaching was not extreme. Additionally, many areas that suffered bleaching in 1998 had low coral abundance in 2001, so the potential for bleaching was less, as well as the possibility that the remaining corals more resistant to bleaching have survived the 1998 event and/or have recruited from more resistant stock.

Conditions Affecting Bleaching in the Indian Ocean

Variation in coral bleaching among sites in the Indian Ocean has revealed a number of patterns also reported from other parts of the world. Factors observed or deduced for sites in the Indian Ocean are presented below, focusing on physical and oceanographic features that may affect the primary stressors—high temperature and radiation—implicated in El Niño bleaching. Biological interactions and factors are listed separately, but are less known for the Indian Ocean due to lower levels of relevant research compared to other parts of the world.

Local Factors Promoting Bleaching

A number of factors may increase the stress felt by corals at a site, related to enhancing high water temperatures and exposure to light. Both factors will increase stress to shallow back reef coral communities.

- Restricted lagoonal circulation – this causes trapping of water bodies over shallow reef or seagrass and mangrove areas, which then flows out over coral communities. Temperature dynamics of a lagoon in Kenya have been well studied (Kirugara *et al.* 1998), showing that maximum heat transfer to lagoon waters occurs due to the coincidence of spring low tides with maximum sun height at midday. Coincidentally for Kenya, tidal and insolation effects are maximum when the sun is overhead at the equinox (March–April), which also coincides with El Niño peak.
- The exposed reef crests of East African reefs are heated during spring low tides, which warms flooding water resulting in a distinct temperature peak during the rising tide that persists for several days (D. Kirugara). This most strongly affects shallow back reef corals also exposed to high radiation levels.

Local Factors Reducing Bleaching

The following factors have been identified that might reduce the absolute magnitude of the El Niño related high temperature anomaly, thereby reducing the stress that causes bleaching.

- Upwelling of cooler water due to continental shelf and/or reef bank topography—Zanzibar (C. Muhando)
- Temperature loss through exchange and mixing of water along fore reefs and in lagoon channels, and potentially with the air in shallow bays—numerous sites; particularly noted for Quirimbass, Mozambique and Kiunga, Kenya.
- Shading by turbid water conditions reducing penetration of harmful ultraviolet radiation—numerous sites; also noted for channels and estuarine reefs in Quirimbass, Mozambique and Kiunga, Kenya, where water mixing and exchange may also be significant.
- Cyclones causing reduced water heating by high cloud cover, and mixing with deeper waters—Mauritius (J. Turner)

Ecological Factors Interacting with Bleaching

Many reefs in the Indian Ocean are already degraded by a range of threats in addition to El Niño related coral bleaching. Principal among these are overfishing and sedimentation, and, more locally, tourism and land-based pollution. Observations so far reported on the interactions of these factors with bleaching have revealed the following:

- Reefs previously degraded by overfishing usually have a coral community dominated by opportunistic and minor coral species. Some of these suffered high bleaching and mortality levels (e.g. *Pocillopora, Stylophora,* branching forms of *Porites*) while others were only slightly affected (e.g. *Cyphastrea, Coscinarea*, other small faviids). On the whole, loss of species and decreased coral cover of degraded reefs was minor, compared to that of healthier reefs.

Marine Protected Areas in the Indian Ocean

The first Marine Protected Areas in the Indian Ocean related to coral reefs were established in Kenya by the Wildlife Conservation and Management Department (now the Kenya Wildlife Service) in 1968. Setting the stage for other coral reef MPAs until the 1980s, the primary objectives of management in these early MPAs were species conservation and tourism. With increasing attention to local communities and needs of subsistence users, MPAs in the 1990s have been established with added goals of managing fisheries and other resource uses, returning benefits directly and indirectly to user communities. Table 2 lists the coral reef MPAs in the Indian Ocean, with notes, where known, on their primary objectives and context.

The table lists a total of 86 named protected areas or management units. The precise number of MPAs in the western Indian Ocean depends on the accepted definition of an MPA, with a count of 69 for the region covered here (Kelleher *et al* 1995; McClanahan 1999). The type of management regime as well as the effectiveness of management ranges greatly among these sites, from full protection through no-take regulations, through regulated use in community-based management, resource regulation and recreational use, to no management (McClanahan 1999). At the regional level, both IUCN and WWF have major marine programs providing assistance in the initiation and management of MPAs.

There is considerable potential for adaptation within this MPA network to include design aspects related to coral bleaching and resilience. In addition to biophysical assessment of how to incorporate coral bleaching into MPA management, effort should be directed towards a consultative process with the responsible agencies for these MPAs to determine appropriate policy and institutional mechanisms for incorporating coral bleaching considerations.

Table 2. Coral reef Marine Protected Areas in the Indian Ocean. Principal sources – Muthiga *et al.* 1998, Rajasuriya *et al.* 1998, Naim *et al.* 2000, Jennings *et al.* 2000, Gabrie *et al.* 2000.

Area	MPA name/area	Year	Notes
East Africa			
Kenya	Kiunga Marine Reserve	1994	Co-management through consensus management plan.
	Malindi/Watamu Marine Park/Reserve	1968	Central management, Effective
	Mombasa Marine Park and Reserve	1989	Central management, Effective
	Diani Marine Reserve	1994	MPA management not implemented. New ICZM project in 2000
	Kisite/Mpunguti Marine Park/Reserve	1974	Central management, Effective
Tanzania	Maziwi (Tanga)	1975	No management
	Tanga Coral Gardens Marine Reserve	1998	District-level management, 4 village-designated reef reserves, Tanga Coastal Zone Management Project (assistance through IUCN)
	Misali Conservation Area (Pemba)	1998	In progress, CARE Zanzibar
	Dar-es-Salaam Marine Reserves – Mbudya, Bongoyo, Pangavini, Fungu Yasini	1975	No management
	Mafia Island Marine Park	1994	Effective
	Mnazi bay	2000	New
Zanzibar	Chumbe Island Coral Park	1994	Private, strict management.
	Mnemba Marine protected area	1992	Private
	Menai Bay Conservation Area	1997	Fisheries Division/local communities/WWF
Mozambique	Maputo Reserve		
	Inhaca and Portuguese Islands Biological Reserve		Partial protection
	Bazaruto National Park		Partial protection

Table 2 (Cont.)

Area	MPA name/area	Year	Notes
South Africa	St. Lucia and Maputaland Marine Reserves Aliwal Shoal		Government user management
Islands			
Comoros	Moheli Marine Reserve		Assistance through IUCN
Madagascar	Nosy Antafana National Marine Park	1989	Part of the Mananara-Nord Biosphere Reserve, effective management
	Three marine parks and reserves: Tampolo, Cape Masoala, and Tanjona		Part of National Park of Masoala, managed by ANGAP, CARE and WCS
Mauritius	Fishing reserves – Black river, Blue bay/Le Chaland, Grand Port/Mahébourg, Port-Louis, Rivière du Rempart-Poudre d'or Nature reserves – Cargados Carajos shoals, Ile aux Aigrettes and Ile Marianne, Ile Plate and Ilot Gabriel		
Rodrigues	Nature Reserves - Ile aux Cocos and Ile aux Sables		
Reunion (France)	Fishing reserves – All reef flats, outer slope of Saint-Gilles/ La Saline to 20 m depth, reefs of Cap La Houssaye		
	Nature reserves – Iles Glorieuses, Tromelin, Bassas de India, Europa		Protection status for turtles, sea birds, coconut crabs, guano.
Seychelles	Cousin I.	1968	BirdLife International, Managed & Policed
	Aride I.	1973	Royal Society for Nature Conservation, Managed & Policed
	Ste Anne I.	1973 Policed	Marine Parks Authority, Managed &
	Curieuse I.	1979	Marine Parks Authority, Managed & Policed
	Baie Ternay	1979	Marine Parks Authority, Basic Mgmt
	Port Launay	1979	Marine Parks Authority, Basic Mgmt
	Silhouette I.	1979	Marine Parks Authority, No Mgmt
	Shell reserves in E. Mahé, N. La Digue and N Praslin	1981	None, No Mgmt
	Aldabra Atoll	1981	Seychelles Islands Foundation, Basic Mgmt
	Ile Cocos, Ilot Platte & Ile la Fouche	1997	Marine Parks Authority, Basic Mgmt
	African Banks	1987	Ministry of Defence, No Mgmt
South Asia			
India	Gulf of Kutch Marine National Park		Inadequate protection
	Gulf of Mannar Biosphere Reserve		Inadequate protection. Educational, scientific and recreational objectives.
	Wandur Marine National Park (Andaman Islands)	Reasonable	protection.
	Lakshadweep – one declared National Park		
Maldives	15 protected sites		Mix of private and gov't protection, no known threats prior to bleaching.
Sri Lanka	Hikkaduwa Nature Reserve		Inadequate protection
	Bar Reef Marine Sanctuary		No Mgmt

Monitoring Programs in the Indian Ocean

Coral reef monitoring is being undertaken in all countries of the Indian Ocean, at various levels that depends on local capacity in personnel and institutions, collaborations with external scientists and institutions, and funding levels. National and local monitoring programs are hosted in each country by relevant institutions (universities, research institutes and conservation management agencies). Each country participates in the various regional monitoring networks and initiatives, that are all slowly integrating under the umbrella of the International Coral Reef Initiative and the Global Coral Reef Monitoring Network (see Wilkinson 2000). While not directly dealing with coral reef monitoring, the management-related activities of IUCN and WWF, and once initiated, ICRAN, will provide important frameworks for regionalization of monitoring.

The primary monitoring programs that have relevance above the national level are the following:

Coral Reef Conservation Project (CRCP, Wildlife Conservation Society) – Kenya and parts of northern Tanzania. CRCP maintains the longest continuous monitoring dataset, principally of lagoon reefs, in protected and unprotected reefs, over a period over 10 years, with initial measurements in the mid 1980s.

Indian Ocean Commission – Regional Environment Program. Funded and coordinated through European Union support to Indian Ocean Islands countries (Comoros, Mauritius, Reunion, Madagascar, Seychelles). This started in 1995 and is continuing in 2000/2001 with GEF funding.

CORDIO – Coral Reef Degradation in the Indian Ocean. Funded through Sida/SAREC, World Bank and other Swedish sources and coordinated through subregional offices in East Africa, South Asia and Indian Ocean Islands. CORDIO was started in 1999 to enable a regional assessment of the impact of bleaching in the Indian Ocean, and is evolving towards facilitation and support at the regional level of ICRI programs, including the Global Coral Reef Monitoring Network.

Global Coral Reef Monitoring Network – In the Indian Ocean, GCRMN is coordinated and implemented in three subregions: South Asia (DFID funded program, hosted by SACEP), the Indian Ocean Islands (REP-IOC, supported by EU and now GEF), and East Africa (unsupported until 1999 when CORDIO became the de facto node).

All the regional programs use variations on methods presented in English *et al* (1998) for monitoring of benthic (line transects, point intercept transects, video transects), resource invertebrate (belt transects) and finfish (belt transects) populations. The Islands program has developed a database based on the AIMS ARMDES to ensure compatibility of data samples. Methods used in national programs vary over a wider range due to different training and research collaboration histories, though these are converging towards standard methods through greater regional collaboration and integration.

The selection of reefs as principal monitoring sites has tended to follow implementation plans of MPAs and/or individual focus of different researchers.

Box 1. CORDIO and further monitoring in the Indian Ocean

Now in its third year, CORDIO is evolving from its initial assessments of the impact of the 1998 El Niño on coral reefs of the Indian Ocean, to developing sustainable monitoring integrated in local and national contexts of stakeholders, research, and management. Three primary areas appear to be important in addressing these goals, and are relevant to CORDIO's contribution to the TNC/WWF proposal for mitigating coral bleaching impact through MPA design. These include the recovery dynamics and potential of impacted reefs, mechanisms by which monitoring can be used effectively in management of bleached reefs, and larger scale issues of regional networking and sustainable financing of monitoring and management areas. These are outlined in point-form below, for further discussion.

Recovery of coral reefs

- Recruitment and larval supply – How much is recovery dependent on recruitment and what are the dynamics of coral larvae supply in a context of bleaching-degraded reefs?
- Recruitment surfaces and state
- Regrowth from existing colonies – how much is recovery dependent on regrowth of tissue following partial mortality and/or from deep tissue?
- What is the rate of reef framework destruction relative to recovery processes?
- How do other threats and destructive human activities impact on reef recovery from bleaching?
- Adaptation of corals and zooxanthellae to changing temperature patterns – is this possible and on what time and spatial scales?

Management and utilization of monitoring

- Local vs. global threats – local effects still very significant and can be addressed by management.
- Participatory monitoring and research (with stakeholders) greatly improves application and effectiveness of management actions.
- Direct partnership between managers, scientists, and stakeholders – a direct outcome of participatory monitoring.
- What training and capacity building needs at local levels, and how best to address these?
- How to adapt monitoring to more effectively contribute to and management and evaluation?

Networking more effectively

- Regional and sub-regional networks – filling gaps in coral reef research, monitoring and management. Orientation of support towards site, institutional and/or individual support rather than to larger frameworks
- Adapt "collaborative management" models to develop one for "collaborative monitoring" – involve government, NGOs, local groups, individuals
- Technical support in monitoring methods and databasing.
- Developing more resilient funding through co-funding arrangements linking local nodes and their infrastructure to regional funding and networking.
- Coordination and integration with regional and international initiatives.

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Acknowledgments

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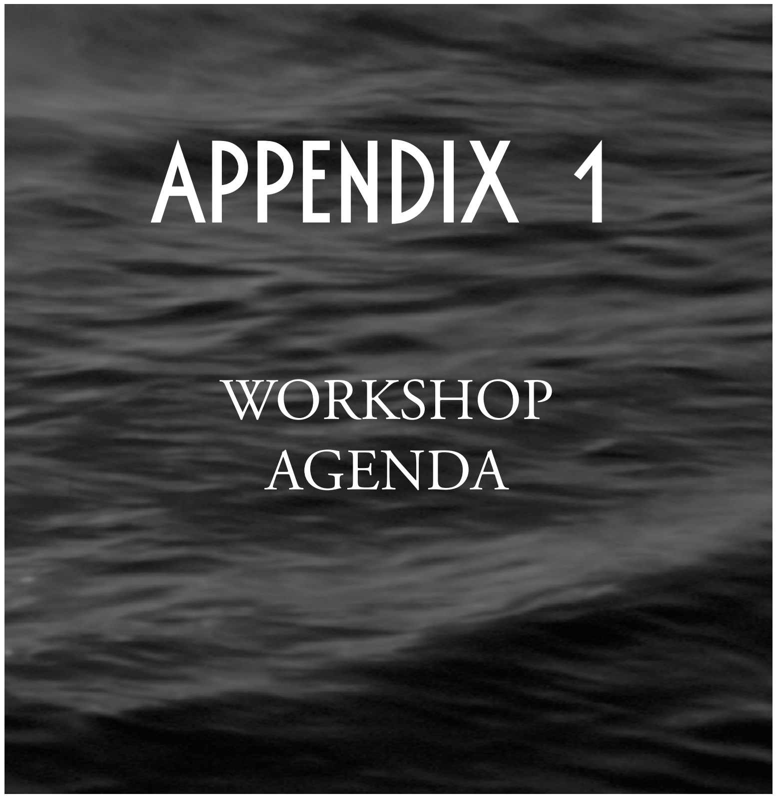
2000). Additional information is compiled from the work and personal communications of several scientists and professionals active in the Indian Ocean. Of particular note I would like to acknowledge the following: L. Bigot, H. Cesar, J. Church, S. Clark, N. Downing, U. Engelhardt, O. Linden, T. McClanahan, S. Mohammed, H. Motta, C. Muhando, L. Pet-Soede, J-P. Quod, A. Rajasuriya, J. Rubens, M. Schleyer, C. Sheppard, D. Souter, T. Spencer, J. Tamelander, K. Teleki, J. Turner, M. Wafar, S. Wells, S. Westmacott, D. Wilhelmsson, C. Wilkinson, and H. Zahir. Many of the preceding scientists are principal authors and by extension I would like to acknowledge their colleagues. Donors that have supported work that has contributed to information in this paper are operating from regional to local scales and are too numerous to name. I will simply note the support provided by Sida/SAREC to CORDIO that has fostered greater regional reporting and contribution to the GCRMN network.


APPENDIX 1
WORKSHOP
AGENDA

Day 1:	**Introduction and Environmental Context**
0900 – 0910	Chairman's Introduction, participant introductions and workshop organization. *Steve Coles & Facilitator*
0910 - 0930	Statement of workshop context, objectives and outputs. *Rod Salm and Gilly Llewellyn*
0930 - 0945	Questions and discussion
0945 - 1000	What we know and what we can do about coral bleaching. *Steve Coles*
1000 - 1030	History of Significant Coral Bleaching Events and Insights Regarding Amelioration. *Peter Glynn*
1030 - 1100	Questions and discussion
1100 - 1115	**Break**
1115 - 1145	Environmental Determinants of Resilience to Coral Bleaching: Implications for Management of Marine Protected Areas. *Jordan West*
1145 - 1215	Questions and discussion
1215 - 1315	**Lunch**
1315 - 1345	Scientific Principles for Establishing MPAs to Alleviate Coral Bleaching and Promote Recovery. *Terry Done*
1345 - 1415	Questions and discussion
1415 - 1430	**Break**
1430 - 1630	Discussion and agreement on environmental factors that assist in mitigating bleaching impact. *All Participants*
1630 - 1700	Day 1 Summary. *Gilly Llewellyn*
Output:	***Agreed list of environmental factors that can mitigate climate-based coral bleaching and related mortality.***

Day 2:	**Measurement and Monitoring, Methods And Applications To Coral Bleaching**
0900 - 0930	Methods and Findings of the Hawaii Coral Reef Monitoring Program (CRAMP) *Paul Jokiel*
0930 - 1000	Questions and Discussion
1000 - 1030	Coral Reef Monitoring in the Indian Ocean. *David Obura*
1030 - 1100	Questions and Discussion
1100 - 1115	**Break**
1115 - 1145	Monitoring of corals, bleaching and protected areas on the Great Barrier Reef. *Jamie Oliver*
1145 - 1215	Questions and Discussion
1215 - 1315	**Lunch**
1315 - 1345	Lessons Learned from the intensification of Coral Bleaching from 1980-2000 in the Florida Keys, USA. *Billy Causey*
1345 - 1415	Questions and Discussion
1415 - 1430	**Break**
1430 - 1630	Discussion and agreement on appropriate monitoring. *All Participants*
1630 - 1700	Day 2 summary. *Steve Coles*
Output:	***Range of acceptable monitoring methods and frequencies to test the hypothesis that MPAs can be used to mitigate coral bleaching and mortality through protecting sites where environmental factors favor coral survival.***

Day 3: MPA Selection, Design, And Management

0830 - 1030	Discussion and incorporation of additional selection criteria and design principles into draft MPA management guidelines. *All Participants*
1030 - 1045	**Break**
1045 - 1200	Discuss and develop a strategy for testing the draft MPA management guidelines at representative sites around the globe including study site selection criteria, existing capacity for implementation, presence of relevant environmental factors, and ensuring comparability of results. *All Participants*
1200 - 1300	**Lunch**
1300 - 1345	Global review of existing coral reef MPAs – will they survive coral bleaching? *All Participants*
1345 - 1500	Discuss and outline the key points to identify where coral reefs will survive bleaching and how to develop a global system of MPAs to protect these sites. *All Participants*
1500 - 1515	**Break**
1515 - 1600	Global system of MPAs (continued)
1600 - 1700	Summing up of workshop results and next steps. *Rod Salm*
1800 - 2000	Closing function

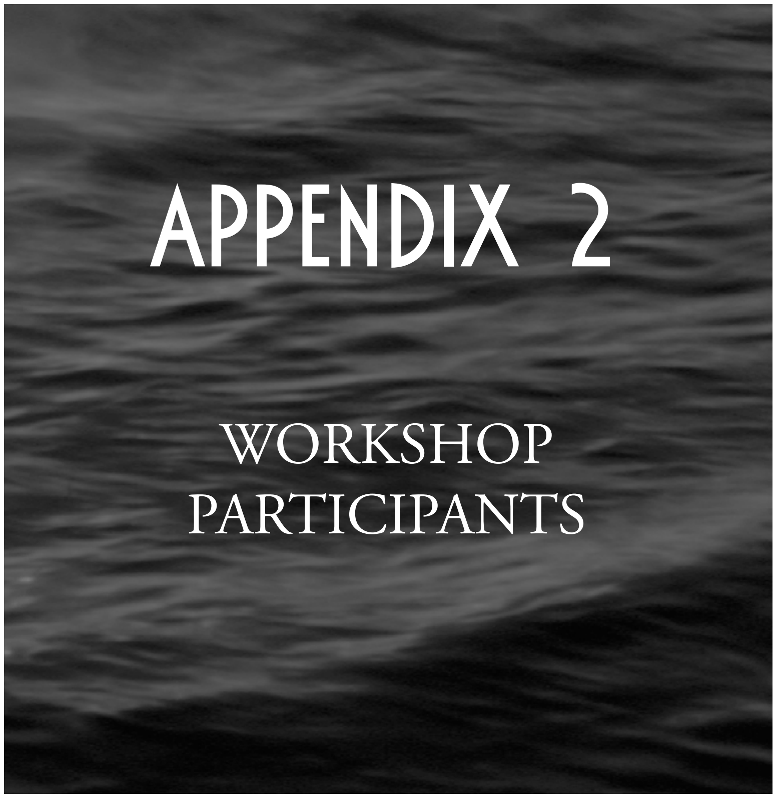
Output:

1) Draft revised MPA management guidelines and additional selection criteria and design principles.

2) Strategy for a global implementation plan including a) location of study sites, b) potential partners, c) centers of monitoring expertise.

3) Outline strategy for establishment of a global system of MPAs that is designed to protect coral reefs with high resilience to bleaching and related mortality.

4) Roles and responsibilities for specific follow-up (next steps)


APPENDIX 2
WORKSHOP
PARTICIPANTS

WORKSHOP PARTICIPANTS

Twelve participants from all geographic areas where coral reefs occur throughout the world attended the workshop. The participants' affiliations and experience are:

Billy Causey – Superintendent, Florida Keys National Marine Sanctuary (senior sanctuary manager in Marine Sanctuary Program, NOAA); P.O. Box 500368, Marathon, FL 33050, USA; billy.causey@noaa.gov; tel. 305-743-2437, fax 305-743-2357.

Athline Clark (workshop facilitator) – Hawaii State Division of Aquatic Resources, Department of Land and Natural Resources, Division of Aquatic Resources (Hawaii point of contact for U.S. Coral Reef Task Force); 1151 Punchbowl St., Honolulu, HI 96813, USA; Athline_M_Clark@exec.state.hi.us; tel. 808-587-0099, fax 808-587-0115

Steve Coles (workshop coordinator and chairman) – Research zoologist, Bishop Museum (nearly 35 years of coral reef research); 1525 Bernice St., Honolulu, HI 96817, USA; slcoles@bishopmuseum.org; tel. 808-847-8256, fax 808-847-8252.

Terry Done – Program leader, Coral Reef Research Centre, Australian Institute of Marine Science; President, International Society for Reef Studies; senior principal research scientist and project leader, Sustaining Living Marine Resources Project); PMB #3, Townsville, QLD 4810, Australia; tdone@aims.gov.au; tel. 617-4753-4344, fax 617-4772-5852.

Peter Glynn – Professor, Division of Marine Biology and Fisheries, Rosenstiel School of Marine and Atmospheric Science, University of Miami (more than 40 years of coral reef research); 4600 Rickenbacker Causeway, Miami, FL 33149, USA; pglynn@rsmas.miami.edu; tel. 305-3614134, fax 305-3614600.

Will Heyman – Marine projects coordinator, The Nature Conservancy (management and research on the Meso-American Barrier Reef); 62 Front St., Punta Gorda, Belize; Will@btl.net. tel. 501-722-503.

Paul Jokiel – Senior researcher, Hawaii Institute of Marine Biology, University of Hawaii (more than 30 years of coral reef research; principal investigator, Coral Reef Assessment and Monitoring Program); P.O. Box 1364, Kaneohe, HI 96744, USA; Jokiel@hawaii.edu; el. 808-236-7440, fax 808-236-7443.

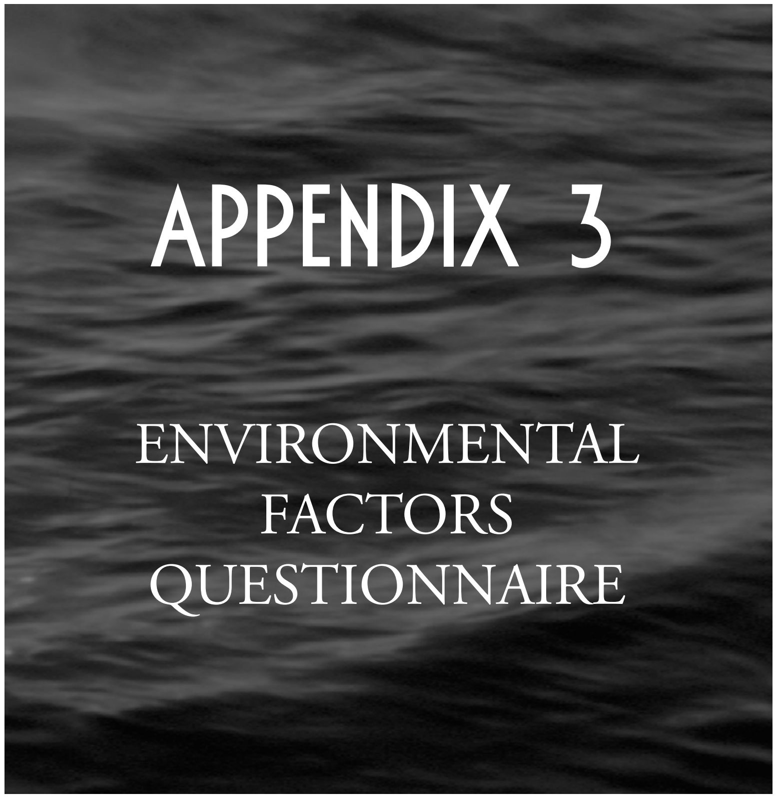
Ghislaine Llewellyn (workshop co-host) – Marine conservation scientist, WWF-US 1250 24th St. NW, Washington, D.C. 20037, USA; Ghislane.llewellyn@wwfus.org; tel. 202-778-9793, fax 202-293-9211.

David Obura – Coordinator, CORDIO-East Africa (Coral Reef Degradation in the Indian Ocean); P.O. Box 10135, Mombasa, Kenya; dobura@africaonline.co.ke; tel./fax 254-011-486473.

Jamie Oliver – Senior scientist, Coral Reef Projects, International Center for Living Aquatic Resources Management (formerly head of monitoring for the Great Barrier Reef Marine Park Authority); P.O. Box 500, Penang 10670, Malaysia; j.oliver@cgiar.org; tel. 606-641-5606, fax 606-643-4463.

Rod Salm (workshop co-host) – Director, Asia Pacific Coastal Marine Program, The Nature Conservancy (30 years coral reef conservation); 923 Nu'uanu Ave., Honolulu, HI 96817, USA; Rsalm@tnc.org; tel. 808-587-6284, fax 808-545-2019.

Jordan West – AAAS/EPA science and engineering fellow, ORD/NCEA/Global Change Research Program, U.S. Environmental Protection Agency; 1200 Pennsylvania Ave. (Mail Code 8601D), Washington, D.C. 20460, USA; west.jordan@epa.gov; tel. 202-564-3384, fax 202-565-0075.


APPENDIX 3
ENVIRONMENTAL
FACTORS
QUESTIONNAIRE

The Nature Conservancy and World Wildlife Fund have established a working group that plans to work with MPA practitioners around the world to evaluate the vulnerability of existing coral reef MPAs to conditions that cause coral bleaching and death, and to recommend application of the new knowledge to management approaches. The assessment is a contribution to the International Biodiversity Observation Year of Diversitas.

Following observations from numerous people that there was considerable variability in the response of reefs during severe bleaching conditions in recent years, it was agreed that the first step in this process should be to make an initial assessment of environmental factors and their contributions to bleaching resistance and resilience. This will be conducted using the results of the enclosed questionnaire, which is being distributed widely. The questionnaire is based upon a list of environmental factors, developed at a workshop at Bishop Museum, Honolulu in May 2001. The listed factors were considered likely to confer resistance to coral bleaching and mortality during bleaching, and to promote resilience or recovery on affected reefs following bleaching events. Responses to the questionnaire will allow the testing of a range of hypotheses that various environmental factors actually confer bleaching resistance and recovery. The process is intended to help define additional criteria that might be factored into the design and selection of new coral reef MPAs.

We therefore seek your input in first step in this process, and hope that you can take the time to complete and return the enclosed questionnaire. We also would appreciate any additional observations you may have on what you consider important environmental factors to consider regarding coral bleaching resistance and recovery.

All people who respond to the questionnaire will be acknowledged, and the compiled data will be subject to analysis of spatial patterns and environmental correlations, with a view to defining good proxies for predicting reefs that are likely to survive best in a period of global warming.

Thank you for your efforts on behalf of the coral reef environment that we all cherish, and we look forward to your response and a continuing interaction.

Terry Done
AIMS

Steve Coles
Bishop Museum

Jamie K. Oliver
ICLARM - World Fish Center

David Obura
CORDIO-East Africa

Rodney V. Salm
The Nature Conservancy

Gilly Llewellyn
World Wildlife Fund

Instructions for Questionnaire

1. Complete a separate questionnaire for each location you would like to report on
2. Enter your answers to the best of your ability - each answer entered will be assumed to be correct within ± 1 category
3. Email, fax or send this questionnaire to the ReefBase Project:

MAIL: PO BOX 500, Penang **FAX:** +60 (0)4 626 5530 **EMAIL:**Reefbase@cgiar.org

Step 1: About me

Name:*

Email:*

Organisation:

Title/Position:

Address:

Expertise:

About myself:

Step 2: Location

Country:

Place Name:

Location: You may specify area boundaries (in decimal degrees)

N

W E

S

or, indicate the center point:

Latitude: Longitude:

Location Description:

Area covered (km2)

Depth of site (m) Min: Max:

Deepest seafloor Within 1 km: Within 10 km:

Part of MPA since: Month/Year

Bleaching occurance: Yes/No

If yes, indicate bleaching period:

Begin (month/year):

End (month/year):

Comments:

Step 3: Biotic

About the pre-bleaching coral community:

Amount of hard coral:	☐ 0% ☐ 30-50%%	☐ 1-10% ☐ >50%	☐ 11-30%
Amount of soft coral:	☐ 0% ☐ 30-50%%	☐ 1-10% ☐ >50%	☐ 11-30%
Amount of fleshy algae:	☐ 0% ☐ 30-50%%	☐ 1-10% ☐ >50%	☐ 11-30%
Amount of "bare":	☐ 0% ☐ 30-50%%	☐ 1-10% ☐ >50%	☐ 11-30%

Diameter of largest 25% massive corals (m): ☐

About coral bleaching:

Amount of hard coral cover bleached:	☐ 0% ☐ 30-50%%	☐ 1-10% ☐ >50%	☐ 11-30%
Amount of hard coral cover died:	☐ 0% ☐ 30-50%%	☐ 1-10% ☐ >50%	☐ 11-30%
Amount of soft coral cover bleached:	☐ 0% ☐ 30-50%%	☐ 1-10% ☐ >50%	☐ 11-30%
Amount of soft coral cover died:	☐ 0% ☐ 30-50%	☐ 1-10% ☐ >50%	☐ 11-30%

About the coral community in 2001-2:

Amount of hard coral:	☐ 0% ☐ 30-50%%	☐ 1-10% ☐ >50%	☐ 11-30%
Amount of soft coral:	☐ 0% ☐ 30-50%%	☐ 1-10% ☐ >50%	☐ 11-30%
Amount of fleshy algae:	☐ 0% ☐ 30-50%%	☐ 1-10% ☐ >50%	☐ 11-30%
Amount of "bare"	☐ 0% ☐ 30-50%%	☐ 1-10% ☐ >50%	☐ 11-30%

Additional Comments

☐

Step 4: Abiotic

About the place's environment:

Strong current exchange:	☐ Not at all true ☐ Mostly true	☐ Somewhat true ☐ Absolutely true
Subject to upwelling:	☐ Not at all true ☐ Mostly true	☐ Somewhat true ☐ Absolutely true
Shaded by aspect or island:	☐ Not at all true ☐ Mostly true	☐ Somewhat true ☐ Absolutely true
Prone to regular turbid water:	☐ Not at all true ☐ Mostly true	☐ Somewhat true ☐ Absolutely true
Prone to regular fresh water:	☐ Not at all true ☐ Mostly true	☐ Somewhat true ☐ Absolutely true
Multilayered coral community giving shade to understory:	☐ Not at all true ☐ Mostly true	☐ Somewhat true ☐ Absolutely true

About potential pre-adaptation:

This place is normally subject to wide temperature range:	☐ Not at all true ☐ Mostly true	☐ Somewhat true ☐ Absolutely true
Corals are often exposed at low tide:	☐ Not at all true ☐ Mostly true	☐ Somewhat true ☐ Absolutely true
Coral diversity is high for this region:	☐ Not at all true ☐ Mostly true	☐ Somewhat true ☐ Absolutely true
Some corals reach centuries in age:	☐ Not at all true ☐ Mostly true	☐ Somewhat true ☐ Absolutely true

About resilience potential:

On a reef well connected to others:	☐ Not at all true ☐ Mostly true	☐ Somewhat true ☐ Absolutely true
Typically strong coral recruitment:	☐ Not at all true ☐ Mostly true	☐ Somewhat true ☐ Absolutely true
High herbivore densities:	☐ Not at all true ☐ Mostly true	☐ Somewhat true ☐ Absolutely true
Low net bio-erosion:	☐ Not at all true ☐ Mostly true	☐ Somewhat true ☐ Absolutely true
Effectively managed reef:	☐ Not at all true ☐ Mostly true	☐ Somewhat true ☐ Absolutely true

Additional comments:

This is the last page. Thank you for filling out this questionnaire.

Back Row (l to r): Jamie Oliver, David Obura, Will Heyman, Rod Salm, Peter Glynn, Billy Causey
Front Row (l to r): Jordan West, Athline Clark, Terry Done, Steve Coles, Paul Jokiel, Ghislaine Llewellyn