A Reef Manager's Guide to
CORAL BLEACHING

Paul Marshall and Heidi Schuttenberg

Australian Government
Great Barrier Reef Marine Park Authority

IUCN
The World Conservation Union

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U.S. Department of Commerce

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Foreword

The biological diversity and productivity of coral reefs underpins the welfare of many societies throughout the world's tropical regions. Coral reefs form the foundation of dive tourism industries, support fisheries and are important to cultural traditions. They play an essential role in buffering coastal communities from storm waves and erosion, and they contain a largely untapped wealth of biochemical resources. Tens of millions of people depend upon reefs for all or part of their livelihood[1], and over a billion people rely on reef-related fisheries worldwide[2].

With coral reefs providing such essential services to humans, the prospect of their continued widespread degradation is of concern. Pollution, habitat destruction, disease and unsustainable fishing have now led to declines in reef condition throughout the world. Against this backdrop of conventional stresses, the threat of mass coral bleaching has recently emerged, leading to what has been widely acknowledged as a 'coral reef crisis'[3, 4].

Mass coral bleaching has affected hundreds to thousands of kilometres of reefs simultaneously. It has caused stress, and in many cases extensive coral mortality, to nearly every coral reef region. In 1997-98 alone, mass bleaching is estimated to have caused over 90 per cent coral mortality to 16 per cent of the world's coral reefs[5, 6]. While strong initial signs of recovery have been observed in some locations, many will take decades to fully recover[7].

Scientists agree that tropical seas will continue to warm over coming decades, increasing both the probability and severity of mass bleaching events[8-11]. These scenarios pose particular challenges to coral reef managers, not the least because the main cause of mass coral bleaching–anomalously warm sea temperatures–is largely beyond their control. Yet, managers can play a critical role in helping reefs survive the threat of coral bleaching. Managers are in a unique position to increase our understanding of the phenomenon of coral bleaching, to take meaningful action during a bleaching event, and to develop strategies to support the natural resilience of reefs in the face of long-term changes in climate.

Because of increasingly strong collaborations between reef managers and scientists, strategies are being developed to directly address the threat of coral bleaching. Management needs and preliminary strategies were first documented in 2000, when the IUCN published *Management of Bleached and Severely Damaged Coral Reefs*[12]. In 2002, the US Coral Reef Task Force called for a collaborative effort to identify actions local managers could take to address the impacts of climate change and mass bleaching on coral reefs. In response, three US government agencies (the National Oceanic and Atmospheric Administration, Environmental Protection Agency, and the Department of the Interior) convened an international workshop entitled 'Coral Reefs, Climate Change and Coral Bleaching' in June 2003. This workshop significantly advanced thinking about the strategies that could support managers in their efforts to respond to coral bleaching.

Around the globe efforts have now begun to improve the prospects of coral reefs by: (1) identifying resilient areas and enhancing their protection, such as in Palau; and (2) implementing strategies to support ecosystem resilience. The Australian Government has implemented strategies to improve the protection of Australia's Great Barrier Reef, including an integrated catchment management scheme and a new comprehensive zoning plan that protects unique areas and biodiversity, and includes 33% of the Great Barrier Reef in no-take areas. Further initiatives to build resilience principles into practical management of coral reefs and other marine ecosystems are under way, including efforts in Florida, USA.

This guide builds on these recent initiatives by bringing together the latest scientific knowledge and management experience to assist managers in responding effectively to mass coral bleaching events. It synthesises science and management information, explores emerging strategies, and informs the ways managers deal with the complex human dimensions of these issues. Importantly, this guide is designed to provide pragmatic, science-based suggestions for adaptive management in this time of change. We commend it to reef managers worldwide, and hope that the experience of implementing the ideas within will further advance scientific knowledge and the practice of coral reef management.

The Hon Ian Campbell, MP
Minister for the Environment
and Heritage
Australia

Vice Admiral Conrad C. Lautenbacher Jr,
US Navy (Ret.)
Under Secretary of Commerce for
Oceans and Atmosphere
USA

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CHAPTER 1

MANAGING FOR MASS CORAL BLEACHING

1. MANAGING FOR MASS CORAL BLEACHING

Mass coral bleaching has affected large spatial areas in every coral reef region in the world and is expected to be a major factor determining future coral reef condition over the next 50 years

The need for a management response to mass coral bleaching is now well established[3, 11, 13]. The incidence and severity of mass coral bleaching events has increased continuously over the last two decades. As a result, almost every reef region in the world has now suffered extensive stress or coral mortality[4, 5]. Observations of these past impacts and studies of expected future trends have prompted leading researchers and managers to declare that coral reefs are in 'crisis'[3, 9]. In keeping with this, the scientific community has suggested that the impacts of mass coral bleaching events, in combination with those from chronic local stressors, will largely determine the condition of coral reefs in the next 50 years[11, 13].

While the need for management has become clear, identifying practicable and effective management responses has proven challenging. Traditional management approaches that focus on minimising or eliminating sources of stress are not applicable to coral bleaching. Coral reef managers are unable to directly mitigate or influence the main cause of mass bleaching: above average water temperatures. This makes mass bleaching a uniquely challenging environmental management problem.

This guide presents a range of strategies for responding to the threat of mass coral bleaching. Importantly, *A Reef Manager's Guide* does not aim to offer a 'cure' for mass bleaching and related impacts. Rather, it draws from a significant and growing body of research striving to develop methods to support the ability of coral reef ecosystems to survive and recover from bleaching events (Section 1.2). Therefore, the *Guide* reviews management actions that can restore and maintain ecosystem resilience, including strategies for developing the knowledge and support that are critical for effective management action.

From a management perspective, mass coral bleaching poses a unique challenge in that its main cause – above average water temperatures – is beyond the control of local reef managers

Figure 1.1 provides an overview of the structure of the *Guide*. The figure illustrates how management strategies are organised around those implemented in response to mass bleaching events (Chapter 2), and those aiming to integrate resilience into long-term management (Chapter 3). Chapter 2 outlines strategies for prediction (Section 2.1) and detection (2.2), assessment of ecological (2.3) and socio-economic (2.4) impacts, management interventions (2.5), and communication (2.6) during mass bleaching events. Chapter 3 discusses how to apply resilience concepts by identifying areas resilient to mass bleaching (3.2), adapting marine protected area design (3.3), implementing broader management measures (3.4), and considering restoration options (3.5). Reviews of the science (Chapter 4) and policy (Chapter 5) that support these management recommendations are also provided.

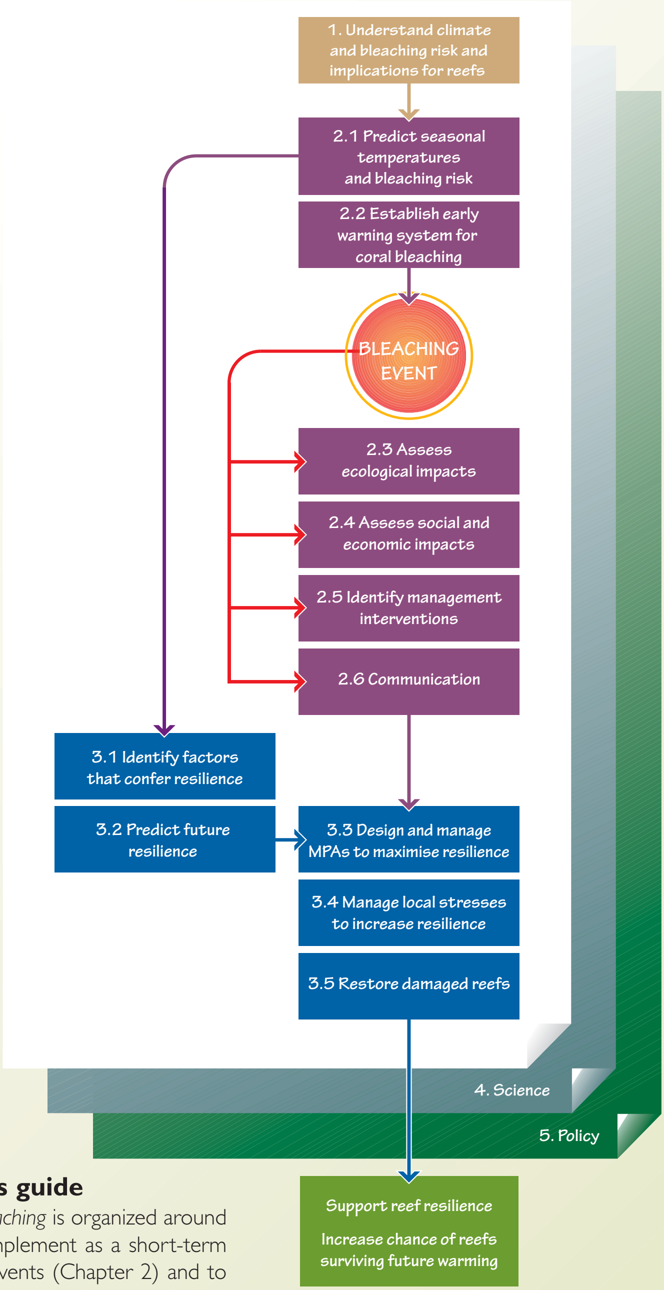

Figure 1.1 How to use this guide

A Reef Manager's Guide to Coral Bleaching is organized around the strategies that managers can implement as a short-term response to mass coral bleaching events (Chapter 2) and to support long-term coral reef resilience (Chapter 3). Background information on the science (Chapter 4) and policies (Chapter 5) that support these management recommendations are also provided. While these actions cannot 'cure' the problem of mass coral bleaching, they offer managers a systematic response to current and future bleaching events that aims to support ecosystem resilience.

This guide attempts to capture the current state of knowledge about managing reefs during a time of changing climate and increased frequency of mass coral bleaching events. More than providing an 'answer' to how best respond to mass bleaching, the full potential of the guide lies in the new ideas and collaborations that it is designed to inspire. With that in mind, readers are encouraged to share their experiences of applying the methods and strategies herein, so that a future edition of this volume might be even more useful.

1.1 Mass bleaching as an emergent issue

The number of regions reporting mass coral bleaching has increased substantially in recent years (Figure 1.2). The implications of mass bleaching received global attention in 1997-98, when increased sea surface temperatures associated with El Niño resulted in extensive bleaching of the world's reefs[6, 14, 15]. Prior to this event, coral bleaching was often considered a local problem–someone else's problem–resulting from localised stresses. The event of 1997-98 distinguished mass coral bleaching from localised events by the global extent of its impacts across reefs and reef regions of different condition, composition and geography. It is attributed to causing mass mortalities of corals to many reef regions[16], in total 'destroying' an estimated 16 per cent of the world's reefs[15].

This event fuelled scientific curiosity about the causes of mass bleaching events and the implications of these events for future coral reef condition. Comparisons of expected sea temperature increases with derived bleaching thresholds suggest that the frequency and severity of mass bleaching events is likely to rise significantly[10, 11] and at a rate substantially faster than that at which coral reef ecosystems are expected to adjust[10, 12]. This implies that, should tropical seas continue to warm, coral reef ecosystems are likely to undergo significant changes. These changes include losses to biological diversity and coral cover[8] as well as economic losses to the fisheries and tourism sectors[13]. They also highlight the need to integrate mass bleaching phenomena into management efforts aimed at sustaining the value of coral reef ecosystems.

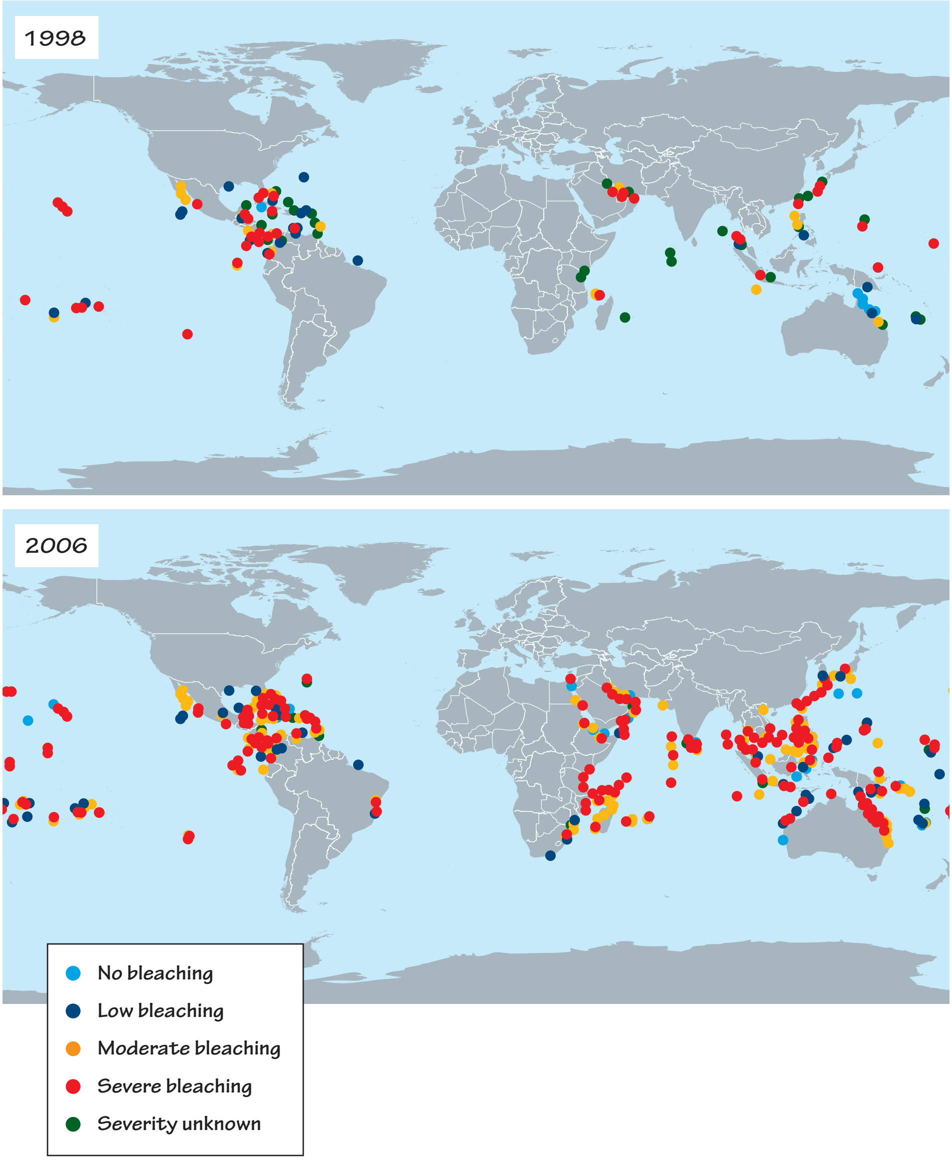

Figure 1.2 Global trends in the extent and severity of mass bleaching

The extent and severity of mass coral bleaching events have increased worldwide over the last decade. Prior to 1998 mass coral bleaching had been recorded in most of the main coral reef regions, but many reef systems had not experienced the effects of severe bleaching. Since 1998 coral bleaching has become a common phenomenon around the world. Every region has now experienced severe bleaching, with many areas suffering significant bleaching-induced mortality.

1.1.1 What is mass coral bleaching?

Although they cover less than 1 per cent of the earth's surface, coral reefs have deposited limestone structures that are home to an estimated one-half to two million species[16]. Ultimately, the ability of coral reefs to support such productivity largely depends on the symbiotic relationship between corals and microscopic algae, zooxanthellae, which live within their tissues. Corals are strongly dependent on their zooxanthellae, which provide up to 90 per cent of their energy requirements[17]. However, stressful conditions can cause this relationship to break down, resulting in dramatic decreases in the densities of zooxanthellae within the coral tissue. Because the zooxanthellae also provide much of the colour in a coral's tissue, their loss leaves the tissue transparent, revealing the bright white skeleton beneath and giving the coral the appearance of having been 'bleached' (see Box 1.1).

Corals appear white or 'bleached' when the coral animal ejects the colourful microscopic algae that live within its tissues as part of a response to stressful conditions

Box 1.1 What happens during coral bleaching?

The productivity of reefs is ultimately attributable to the symbiotic relationship between the coral polyp and its dinoflagellate algae, known as zooxanthellae, which live packed within the coral's tissues. Under normal conditions, the zooxanthellae perform photosynthesis and provide energy-rich compounds to the coral animal. However, under conditions of increased temperature, the algae are unable to process incoming light without releasing harmful oxygen radicals, similar to those involved in aging. When this happens the coral-algal relationship is disrupted and the zooxanthellae either degenerate in the tissue or are released from the tissue. Consequently, the bright white coral skeleton is visible through the unpigmented tissue, making the corals appear 'bleached'.

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Under normal conditions microscopic algae, called zooxanthellae, live inside the tissues of the coral animal and provide up to 90 per cent of the coral's energy requirements

At a local scale, many stressors may cause corals to bleach, including storms, disease, sedimentation, cyanide fishing, herbicides, heavy metals, and changes in salinity and temperature[18]. The primary cause of regional, or *mass*, bleaching events is increased sea temperatures[8, 9, 13, 18-20]. Sea temperature increases of 1-2°C above the long term average maximum are all that are required to trigger mass bleaching[9, 23]. Both the intensity and duration of temperature anomalies are important in determining the timing and severity of bleaching responses. Higher temperatures can cause bleaching over a shorter exposure time, while lower temperatures require longer exposure times. While temperature is the trigger for bleaching, light also influences the severity of bleaching impacts[24].

The types of conditions that cause the rapid warming of waters characteristic of spatially extensive bleaching events often coincide with calm, clear conditions that increase light penetration. For this reason, shaded corals are likely to bleach less severely than corals exposed to normal light levels during heat stress.

Bleached corals are still living and, if stressful conditions subside soon enough, zooxanthellae can repopulate their tissues and the corals can survive the bleaching event (Figure 1.3). However, even corals that survive are likely to experience reduced growth rates[25, 114], decreased reproductive capacity[26], and increased susceptibility to diseases[27]. Bleaching can cause the death of corals if stresses are severe or persistent. In many cases, bleaching events have caused significant mortality of corals (>90% of corals killed)[7].


Healthy coral


Bleached coral


Dead coral

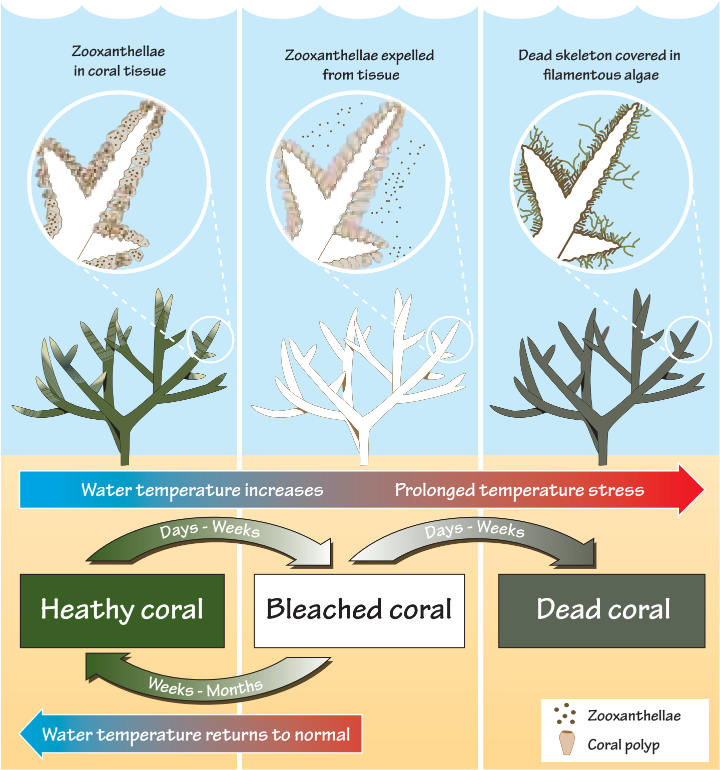


Figure 1.3 Stages in mass coral bleaching
During mass coral bleaching, water temperature increases above a critical threshold, typically over a large area. Under these stressful conditions, corals begin to lose their zooxanthallae, eventually appearing 'bleached'. At this stage, the bleached corals are still living and, if stressful conditions subside soon enough, they can regain their zooxanthallae. In this case, corals can survive, but are likely to suffer sub-lethal impacts, such as reduced rates of growth and reproduction and increased susceptibility to diseases. However, should temperature stress continue, corals are likely to die. Where mass coral bleaching causes high levels of coral mortality, these ecosystems typically take years to decades to recover.

1.1.2 Trends in mass bleaching and coral reef condition

The global reach of the 1997-98 bleaching event has raised serious concerns about the future of coral reefs. To determine the threat posed by future bleaching events, researchers have compared known temperature thresholds for coral bleaching with projected sea temperature increases under various climate change scenarios. These studies have shown that sea temperatures may soon regularly exceed bleaching thresholds, making severe bleaching events an annual occurrence on many reefs worldwide[9, 28]. The projected levels of temperature stress also exceed the values known to cause major coral mortality[28-30].

Corals and coral reef ecosystems exist in a wide range of environmental conditions, suggesting that they have some capacity to adapt to changing sea temperatures. In the Arabian Gulf, corals do not bleach until they reach temperatures 10°C higher than summer maxima in cooler regions within the same species' range[11]. However, the projected rate and magnitude of temperature increase will rapidly exceed the conditions under which coral reefs have flourished over the past half-million years[11], and there is growing evidence that corals will be unlikely to adapt fast enough to keep pace with even the most conservative climate change projections[9, 23, 28].

The implication of these conclusions is that the rate and extent of mass coral bleaching is likely to increase in the future, causing further degradation to coral reef ecosystems[9]. As a consequence, there is likely to be a shift towards reef communities that have lower biological diversity and less coral cover, and are dominated by coral taxa that are either resistant or inherently resilient[9, 11, 31]. Corals and coral reefs have survived massive changes in their physical and chemical environment over the past half-million years, and they are unlikely to disappear altogether, even under extreme climate scenarios. However, the condition of reefs and the ecosystem services that they provide are likely to significantly deteriorate as a result of coral bleaching over the next few decades to centuries. Chapter 4 presents a more detailed discussion about the science related to coral reefs and mass bleaching.

Mass coral bleaching events are expected to increase in extent and severity, causing losses to biological diversity and coral cover as well as economic losses to the tourism and fisheries sectors

1.1.3 Socioeconomic and management implications

It is well documented that coral reef degradation can result in socioeconomic losses through impacts to fisheries, tourism, and other ecosystem services, such as shoreline protection[32-36]. The extent to which mass coral bleaching affects people is determined by several variables, including the extent to which bleaching results in coral mortality, the ways in which human communities use the reef areas that have been affected, and the flexibility of human communities to shift their dependence off coral reefs when ecological degradation occurs. These variables may provide a useful focus to management and policy efforts aiming to reduce the impacts of mass bleaching on dependent human communities. For example, knowledge about levels of resource-dependency among local fishing communities can help policy-makers select response strategies following severe bleaching that will not only minimise economic impacts, but also be consistent with social and cultural values and practices. This, in turn, maximises the likelihood that those affected will support the management initiatives, increasing their sustainability.

Some studies have documented or predicted considerable economic losses because of mass coral bleaching. For example, a study on the 1998 mass bleaching event estimated a loss of US$700–8200 million in net present value terms for the Indian Ocean[37]. Importantly, it is expected that the timing and extent of economic impacts will be closely related to the severity of mass bleaching events. The total costs of severe bleaching globally over a 50-year time horizon are estimated at over US$84 billion in net present value, using a three per cent discount rate[38]. For moderate bleaching, this number is US$20 billion[38]. In the Great Barrier Reef in Australia, bleaching-related reef damage is predicted to cause losses to the tourism industry alone of between US$95.5 million and $293.5 million by 2020[28].

Another central consideration in documenting and managing for mass bleaching is the complexity of these systems. In particular, managers are realising that it is important to consider the cumulative impacts of simultaneous threats to coral reefs. Efforts have been made to document the specific socio-economic losses that result from mass coral bleaching[31-35]. These studies demonstrate the difficulty of isolating the effects of single phenomena against a backdrop of multiple influences and the adaptability of human systems. They also identify a number of confounding factors that make it difficult to isolate impacts related to bleaching from ecological degradation due to other natural disturbances (for example cyclones), changes in fishing practices, and changes in tourism visitation resulting from geopolitical issues (such as terrorism)[37]. While these complex interactions are challenging, they may also provide opportunities to strengthen the resilience of coral reef ecosystems and the human communities that depend on them.

1.2 A strategy for management

Our understanding of mass bleaching suggests that the future condition of coral reefs will be largely influenced by two factors: (1) the rate and extent of sea temperature increases[9,13] and (2) the resilience of coral reef ecosystems[11, 39, 40]. The rate and extent of warming will determine the window of opportunity for reefs to adjust through acclimatisation, adaptation, and other ecological shifts. For example, fewer and less intense temperature anomalies will reduce the frequency and severity of bleaching events, and slower rates of warming will allow more time for reefs to recover between events that do occur. These relationships mean that the effectiveness of broader efforts to address the rate and extent of warming will have significant implications for local management initiatives[28, 40].

However, such efforts are largely a matter for national and international policy and lie beyond the scope of this volume. The focus of this guide is on the second factor: What actions can local coral reef managers implement to restore and maintain the natural resilience of their coral reefs.

The future condition of coral reefs will be largely influenced by two factors: (1) the rate and extent of increased temperature stress and (2) the resilience of coral reef ecosystems

1.2.1 Opportunities to minimise mass coral bleaching impacts

Four successive conditions determine the ultimate impacts of mass coral bleaching following a regional heat stress event, and each can be considered a potential focus for management action, as shown in Figure 1.4. The first condition, bleaching resistance, determines the extent to which corals within the area of a regional heat stress event are bleached. If corals do bleach, the second condition, coral tolerance, determines the extent to which corals either die or regain their zooxanthellae and survive. If there is widespread coral mortality, the third condition, reef recovery, determines the extent to which the coral reef ecosystem is able to recover and maintain the characteristics of a coral-dominated ecosystem. Finally, if the coral reef ecosystem remains degraded, then the fourth condition, human adaptive capacity, determines the extent to which human communities will experience negative socioeconomic consequences.

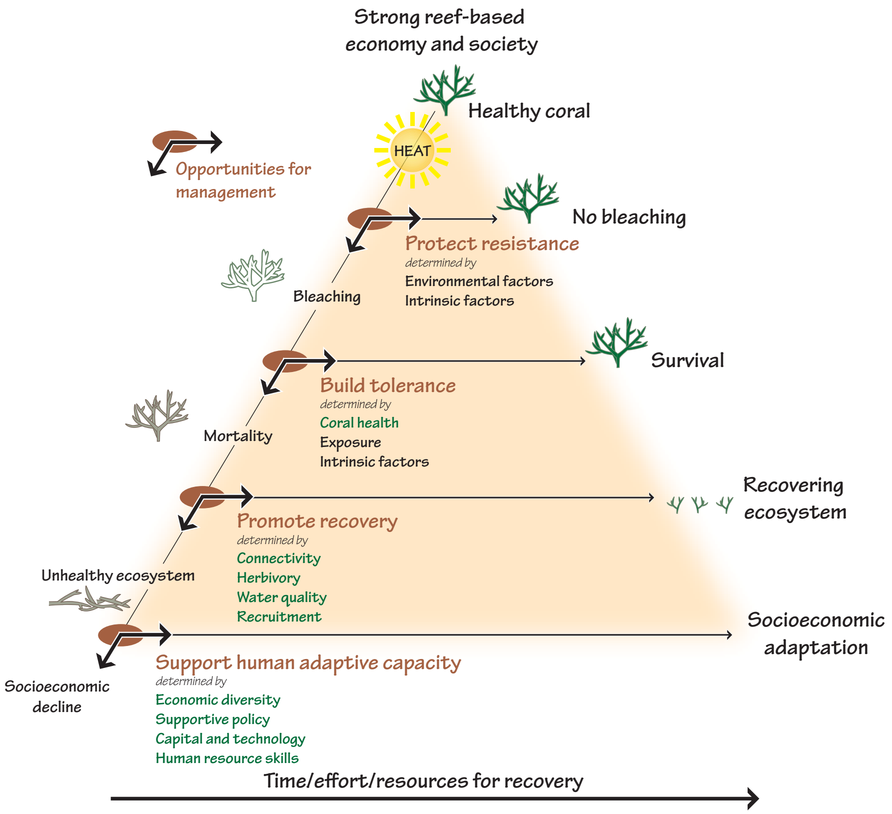


Figure 1.4 Opportunities for management intervention

Four conditions determine the outcome of stressful temperatures for coral reefs: bleaching resistance, coral tolerance, reef recovery and human adaptive capacity. Each of these is influenced by a suite of factors that, in combination, determine the resilience or vulnerability of the system. Factors that can be influenced by local management actions are highlighted in green. Factors shown in black cannot be changed through local management interventions, but can be incorporated in the design and placement of management initiatives to enhance ecosystem resilience. Adapted from Obura (2005)[88].

Each of these conditions is influenced by a suite of factors that affect the resilience or vulnerability of these systems. Factors vary in the extent to which they can be changed through management interventions, their relative influence, and the scale (coral, ecosystem, or human community) at which they are expressed. Factors that can be influenced by local management actions are highlighted in green in Figure 1.4. Factors shown in black cannot generally be changed by management interventions; however, both types of factors can be incorporated into management strategies. Black factors can be utilised in the design and placement of management initiatives. Green factors can be changed by management interventions in order to promote system resilience.

The remainder of this chapter briefly describes opportunities to minimise the impacts of mass bleaching events through strategies that promote the first three conditions: bleaching resistance, bleaching tolerance, and reef recovery. These concepts form the basis for the management interventions presented in Chapters 2 and 3, and the science behind them is discussed in detail in Chapter 4. The fourth condition, human resource dependency, is considered further in Section 2.4.

Identifying and protecting coral reef areas that are naturally resistant to temperature-related bleaching can help to create a network of refuges to 're-seed' areas damaged by mass coral bleaching

Strategies for promoting coral resistance. Environmental and intrinsic factors are likely to be the main influences on whether or not corals bleach[23]. The effects of coral bleaching are characteristically patchy, with different types of corals and corals in different locations frequently showing different responses during a bleaching event[18, 118]. Local environmental conditions are important because shading or exposure to cooler waters can reduce the risk of bleaching. The individual history and genetic composition of both the coral animal and its symbiotic zooxanthellae also influence resistance to bleaching[79, 80]. Section 3.2 discusses how knowledge of these factors can help managers identify corals or reef areas that are likely to be more resistant to mass bleaching. Once identified, management measures can be implemented to minimise localised threats to these areas, thereby creating a network of refugia to 're-seed' reefs more susceptible to bleaching (see Sections 3.3-3.4).

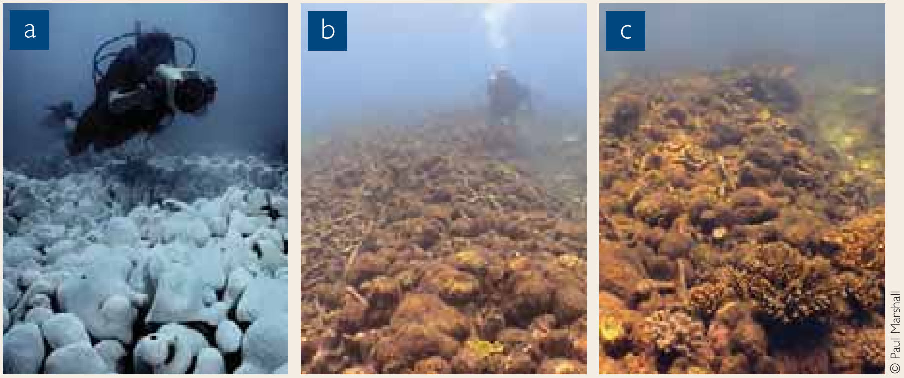
Reducing or eliminating other stressors will be an important factor in increasing coral survival

Strategies for promoting coral survivorship. The difference between significant coral survival and coral mortality during mass bleaching events equates to the difference between years and decades in terms of reef recovery time (see Box 1.2). For this reason, promoting coral survival during bleaching events is likely to be a particularly efficient focus for management. Well-established ecological principles suggest that reducing or eliminating other stressors to coral can be important for increasing coral survival during temperature-related bleaching events (see Section 2.5.1). When bleached, corals effectively enter a period of starvation due to the loss of their energy-providing zooxanthellae. The condition of a coral when it enters this stressed state is likely to determine its ability to endure a bleaching-induced 'famine'[41] long enough for temperatures and zooxanthellae densities to return to normal.

Above a certain threshold of sea temperature, however, heat stress may cause direct physiological damage to corals, exceeding any nutritional concerns and leading to death[9]. Both environmental and intrinsic factors are important in determining the extent to which this happens. As before, local environmental factors have an important influence on the amount of heat stress to which a coral is exposed. Similarly, intrinsic factors, such as genetics, influence the threshold temperature at which a coral dies, with some species able to tolerate higher temperatures than others. These factors contribute to patterns of natural resilience that can be built into management planning (Sections 3.2 and 3.3).

Box 1.2 Recovery after bleaching mortality

Reefs suffering high coral mortality require a time-consuming recovery process of recolonisation by coral larvae and asexual reproduction (such as by fragmentation) of corals that survived the event. Even under ideal conditions, coral recovery is slow and may take decades. Importantly, successful recovery depends on many conditions including the presence and sufficient connectivity of 'source' reefs to generate new larvae, good water quality that allows spawning and recruitment to succeed, and both strong herbivore populations and good water quality to ensure suitable substrate is available for new coral recruits. The ecological requirements for successful coral reef recovery highlight the importance of considering management of local and global stressors together, since they interact to determine outcomes for reefs.



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Photos of the reef at Pelorus Island on the Great Barrier Reef during and after severe bleaching-induced mortality. (a) This large stand of *Goniopora*, or daytime coral, was completely bleached during the summer of 1998. It died shortly after. (b) Despite healthy conditions and effective control of algae by herbivores, only the earliest stages of recovery were evident by 2002. (c) There was good coral recruitment by 2004, but full recovery is likely to take decades.

Strategies for promoting reef recovery. There is ample evidence that coral ecosystems in good condition will recover from mortality more successfully than will degraded ecosystems. Healthy reef ecosystems are better able to provide the conditions required for the recruitment, survival and growth of new corals after established corals have been killed by bleaching[11, 42, 44]. Recovery requires a source of new coral recruits and suitable substrate for the settlement and survival of larval corals. Good water quality, an abundant and diverse community of herbivorous fishes, and high coral cover are key aspects of ecosystem quality that facilitate recovery[44, 45]. Ecological modelling and empirical observations have indicated that the original extent of coral cover and the abundance of herbivorous fishes are two of the most important factors determining future reef condition under scenarios of repeated mass bleaching[31, 46, 47]. Therefore, management of local fisheries, water quality, and tourism strongly influence both the rate and success of recovery and future coral reef resilience. Biological diversity and connectivity among reefs are also important considerations that promote reef recovery[39]. These factors are discussed further in Section 3.1.

Healthy reef ecosystems are better able to provide the conditions required for the recruitment, survival and growth of new corals to replace those killed by bleaching

In the Great Barrier Reef in Australia, bleaching-related damage is predicted to cause losses to the tourism industry alone of between US$95.5 million and $293.5 million by 2020

1.2.2 Integrating resilience into broader reef management

Although often discussed in isolation, the interactions between local and global threats will define the future of reefs[9, 11, 13]. The cumulative impacts of multiple, simultaneous threats, are at the heart of key management questions. Understanding the complexity of the threats facing coral reefs is particularly important for: maximising cost-benefit when determining where management efforts should be focussed; making credible predictions about the effectiveness of management interventions aimed solely at local stressors; and assessing the ability of coral reefs to continue to provide goods and services of value to humans under plausible climate change scenarios. From a management perspective, the interaction of local and global stressors can be considered from two perspectives:

1. How can control of local stressors be used to increase reef resilience?
2. What does the additional threat of mass bleaching mean for management of 'traditional' coral reef issues, such as water quality, fishing, and tourism?

Corals will become more vulnerable to local threats as oceans warm and corals are confronted with global and local stressors at the same time

Based on projections of future ocean warming, corals are likely to be closer to critical thresholds, making them even more vulnerable to local stresses. This is likely to translate to a reduction in resilience suggesting that managers may need to re-evaluate the adequacy of current approaches to management of coastal developments, water quality, fisheries, and tourism. In particular, reef managers should consider the potential costs and benefits of restricting the timing or intensity of activities in order to minimise sources of additional stress to corals and associated organisms, especially during bleaching events. Other management implications are discussed in Section 3.4.

CHAPTER 2

RESPONDING TO A MASS CORAL BLEACHING EVENT

2. RESPONDING TO A MASS CORAL BLEACHING EVENT

This chapter outlines five actions managers can take to prepare and respond during bleaching events. Many of these actions aim to help managers develop and communicate reliable information about the impacts of a mass bleaching event. These strategies do not provide a 'cure' to mass coral bleaching. However, managers have found that implementing these actions during and after bleaching events can improve the overall effectiveness of coral reef management. Specifically, managers can gain and maintain critical support from decision-makers and other stakeholders by raising awareness and advancing scientific understanding about the patterns and impacts of coral bleaching and the importance of ecosystem resilience to the future of coral reefs.

2.1 Developing a bleaching response plan

Responding to a mass bleaching event is a demanding task with numerous challenges; managers who have planned in advance for events will have an advantage

Like any contingency plan, developing a 'Coral Bleaching Response Plan' allows managers to respond more effectively during the rapid onset of a mass bleaching event. At its most basic level, the plan should identify the goal of the response, specific steps that will be taken to meet the goal, and resources required to implement the response. Plans can be created to meet the needs of any reef manager, taking into account available resources, staff capacity, management authority, and the characteristics of local coral reef systems. Table 2.1 provides some examples of activities that can be included in bleaching response plans depending on available resources.

The Great Barrier Reef Marine Park Authority (GBRMPA) Bleaching Response Plan provides another example (Appendix). The GBRMPA plan includes procedures for prediction, ecological assessment, and communication of mass bleaching impacts. These procedures consist of routine, responsive, and strategic tasks. Routine tasks occur throughout the summer season, whether or not there is a bleaching event. For example, routine tasks include the monitoring of environmental conditions and frequently updating assessments of bleaching risk.

Responsive tasks are only implemented if a bleaching event occurs. Responsive tasks include rapid assessment of ecological impacts and increased communication activities, which can include briefings for both senior managers and the media. Because it can be difficult to decide exactly when a bleaching event has started, the GBRMPA plan outlines specific thresholds that trigger each type of responsive task. For example, when bleaching thresholds are exceeded at multiple sites, a structured aerial survey is undertaken to determine the spatial extent and severity of bleaching in the region.

Table 2.1 Examples of tasks from four categories of bleaching response actions under three different resource scenarios

Resource Availability		
Low	Medium	High
Early warning system (Section 2.2)		
• Check NOAA Coral Watch reports • Volunteer network to detect the onset of bleaching	• Check NOAA Coral Watch reports • Check local weather forecasts • Initiate sea temperature monitoring program using in situ loggers • Develop and monitor reef-specific bleaching temperature thresholds	• Check NOAA Coral Watch reports • Work with local weather forecasters to develop forecasts of conditions likely to induce bleaching • Initiate sea temperature monitoring program using in situ loggers • Establish stations for real-time sea temperature measurement • Develop and monitor reef-specific bleaching temperature thresholds
Impact assessment (Section 2.3-2.4)		
• Volunteer network to estimate the severity of bleaching, as well as report coral types affected • Timed swims	• Volunteer network to estimate the severity of bleaching, as well as report coral types affected • Manta tows • LIT/Belt transects	• Volunteer network to estimate the severity of bleaching, as well as report coral types affected • Aerial Surveys • Video Transects • Socioeconomic impact studies
Management interventions (Section 2.5)		
• Take steps to protect herbivore populations and water quality through appropriate actions (eg facilitating community-based protected areas, installing latrines, limiting land-clearing, etc)	• Take steps to protect herbivore populations and water quality through appropriate actions (eg implement fishery regulations, address harmful land-use practices) • Consider restricting potentially stressful impacts from coastal development and recreational use during periods of high water temperature	• Take steps to protect herbivore populations and water quality through appropriate actions (eg implement fishery regulations, address harmful land-use practices) • Consider restricting potentially stressful impacts from coastal development and recreational use during periods of high water temperature
Communication (Section 2.6)		
• Talk to community members and local media about mass bleaching • Brief senior decision-makers • Meet with key stakeholders, local media, and colleagues • Send email updates	• Brief senior decision-makers • Meet with key stakeholders, local media, and colleagues • Send email updates	• Brief senior decision-makers • Meet key stakeholders, local media, and colleagues • Send email updates • Update websites • Make informative publications readily accessible to the public • Offer seminars • Develop and implement an education program for local schools

Strategic tasks may be taken at any time to strengthen a bleaching response or support long-term coral reef resilience (see Chapter 3). Strategic activities can include building capacity, securing funding, raising awareness, developing professional networks to exchange information, establishing policies that support bleaching response, or implementing management initiatives to increase protection for or restore factors that confer resilience to the system.

The remainder of Chapter 2 provides detail of the actions that can be taken as part of a comprehensive response to a mass bleaching event. Managers may wish to take ideas from these sections for their own bleaching response plans.

2.2 Predicting mass coral bleaching

The strong relationship between temperature and the onset of mass bleaching allows managers to estimate the risk of coral bleaching based on forecast and observed climatic conditions and sea temperatures. This ability allows a manager to be the source of timely and credible information about bleaching risk for decision-makers, stakeholders and the media. Additionally, it provides important information needed for impact assessment and management responses. This section describes the key approaches available to predict the probability and severity of a mass coral bleaching event during high risk bleaching periods, when sea temperatures reach their annual maximum (see Figure 2.1).

The strong relationship between temperature and the onset of mass bleaching allows managers to estimate the risk of coral bleaching

Figure 2.1 Environmental conditions and information sources used to estimate bleaching risk

Mass coral bleaching is preceded by environmental conditions that can be tracked to provide managers with an effective early warning system for bleaching events. In orange and red, these conditions are described hierarchically from general situations that may suggest an increased risk of bleaching to specific circumstances that correspond to a high risk of bleaching. Readily available information sources are listed to the right of each environmental condition and further described in the text.

2.2.1 Climatic conditions

Large-scale climate patterns. Sea temperature is the most reliable predictor of the occurrence and severity of large-scale coral bleaching events[9, 18, 19]. An understanding of the factors that influence sea temperature has the potential to enable managers to predict the probability of occurrence and severity of a bleaching event. In theory, the relationship between climate patterns, seawater heating, and mass bleaching should provide a mechanism for such predictions. In particular, the weather patterns associated with phenomena such as the El Niño Southern Oscillation or the Pacific Decadal Oscillation can be associated with regional and local warming sea temperatures[48]. A dramatic example of the potential influence of large-scale climate patterns is the 1997-98 global mass bleaching event, which was associated with an extreme El Niño event.

Despite the importance of large-scale climate patterns in determining local conditions, precise predictions of bleaching risk remain difficult. Many local and regional factors also affect the rate and duration of sea temperature increases, including regional ocean currents, cloud cover and winds. The interplay of local, regional and global factors make it important that managers do not place too much emphasis on using single variables, such as ENSO, as their only measure of bleaching risk[49]. The extent to which the complex interactions of different oceanic and atmospheric phenomena can be incorporated into predictive models for coral bleaching will vary from place to place depending on climate dynamics and the knowledge and expertise of local forecasting systems.

However, precise predictions are not necessary for many management applications. Reef managers may still get a very useful indication of whether their region is likely to experience increased heating in coming months based on climate predictions. For example, the El Niño Southern Oscillation (ENSO) index is used to indicate the probability of above-average air temperatures, and extent to which the monsoon trough will develop (which affects cloud cover and winds) over the Great Barrier Reef (GBR). These seasonal forecasts are used by the Great Barrier Reef Marine Park Authority to assess the likelihood that conditions conducive to anomalous warming of the waters are going to occur in or around the Great Barrier Reef.

Managers may find it useful to discuss the effects of climatic factors on sea temperatures with local oceanographers, meteorologists and other scientists. For locations where links between climate and sea temperatures are known, reports and information on large-scale climate phenomena can be a useful aid to predicting bleaching risk. An example of a useful source of information is the ENSO Reporting Centre, which provides ENSO forecasts through email updates and a comprehensive website:
www.cpc.ncep.noaa.gov/products/analysis_monitoring/enso_advisory

Weather. Weather patterns also provide a useful indication of whether bleaching risk is increasing or decreasing. Longer-term predictions, such as seasonal forecasts, can be used to assess the probability of weather conditions that contribute to increasing sea temperatures occurring over timescales of weeks to months. For example, seasonal outlooks for the hot season that predict above-average air temperatures and decreased storm activity indicate that there is an increased probability of conditions that can lead to stressful sea temperatures.

Shorter-term predictions, such as weekly weather forecasts, indicate whether sea temperatures will increase or decrease in coming days and weeks. The risk of mass bleaching is higher when forecasts are for high air temperatures and extended periods of clear skies, low wind and neap tides[50]. In contrast, forecasts for stormy conditions with cooler air temperatures, high cloud cover and strong winds indicate that sea temperatures may stabilise or decrease over the coming week. Table 2.2 summarises the major climatic variables that are known to influence sea temperatures and thus the risk of a mass bleaching event occurring.

The risk of mass bleaching is higher when weather forecasts are for high air temperatures and extended periods of low wind and low cloud cover

Table 2.2 Climate variables and their influence on bleaching risk

Climate variable	Implications for bleaching risk
ENSO	El Niño conditions increase sea temperatures in the Indian and central to eastern Pacific Oceans, and may increase the chances of stable hot conditions in the atmosphere in some reef regions. La Niña conditions may increase temperatures in the western Pacific.
Air temperature	Hotter air temperatures enhance the warming effect of the sun.
Cloud cover	Low cloud cover increases heating of surface waters. However, middle to high level cloud cover acts as a shade and lessens the heating effects of the sun.
Wind	Low winds increase heating of surface waters. However, strong winds (and waves) have the ability to mix water to great depths, which reduces surface water temperature. A change in wind direction resulting in cooler winds can also dramatically reduce surface water temperatures.
Tidal currents	Strong tidal currents coincident with spring tides increase mixing and reduce temperatures of surface waters.

2.2.2 Sea temperatures

Once atmospheric conditions suggest the development of unusually warm conditions, measurements of sea temperatures provide a more direct indication of the potential for mass coral bleaching. Temperature stress can be monitored using satellite imagery and in-water instruments.

Unusually high seawater temperatures are the most direct indicator of bleaching risk and can be monitored using 'HotSpot' images produced from satellite data by NOAA or by local, in-water temperature loggers

Satellite imagery. Coral Reef Watch, a program of the US National Oceanic and Atmospheric Administration (NOAA), has developed three tools that analyse satellite imagery to assess the likelihood of mass coral bleaching events. These products are freely available over the Internet, and include: HotSpot maps, degree heating week (DHW) maps and Tropical Ocean Coral Bleaching indices.

HotSpot and DHW maps are global to regional images that display the intensity and duration of unusually warm sea surface temperatures (SSTs) using remotely sensed data. Both the intensity and duration of heat stress are important factors in predicting the onset and severity of a mass bleaching event. HotSpot maps show the intensity of temperature anomalies with a colour gradation (Figure 2.2). A temperature anomaly is calculated as the difference between the observed sea temperature and the highest temperature expected for a specific location, based on long-term monthly averages. It provides a useful reference point that shows the extent to which current temperatures vary from those that the corals are accustomed to experiencing that time of year. Because different geographical locations vary in their average water temperature, an anomaly of 2°C could mean an actual temperature of 28°C in the Galapagos, but it could mean 34°C in the Red Sea. Despite the differences in absolute water temperatures, conditions are likely to be equally stressful for corals in both locations because the sea temperature anomaly is the same. Anomalies of only 1-2°C can cause mass bleaching.

DHW maps combine the intensity of temperature anomalies, found in the HotSpot maps, with the duration of exposure to provide a composite picture of accumulated temperature stress over the last 12 weeks (Figure 2.3). One DHW is equivalent to one week of SSTs 1°C greater than the expected summertime maximum. Two DHWs are equivalent to two weeks at 1°C above the expected summertime maximum or one week of 2°C above the expected summertime maximum. At four DHW, the Coral Reef Watch program issues a Coral Bleaching Alert that a mass bleaching event may occur. Current research on the GBR suggests that other aspects of a thermal regime, particularly the rate of heat stress accumulation, can also be useful indicators of bleaching risk.

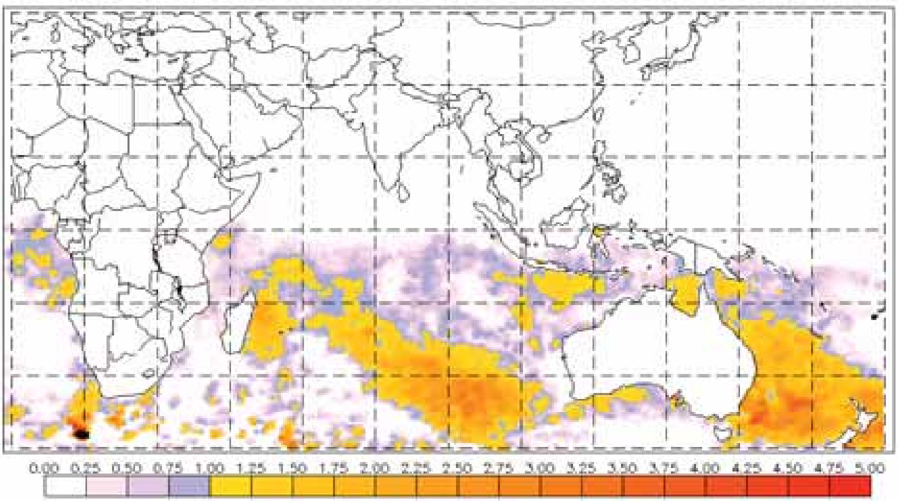

Figure 2.2 NOAA HotSpot map for the eastern hemisphere for 20 February 1998

The colour of the grid cells represents the temperature anomaly in degrees Celsius, as indicated in the legend along the bottom of the map. Temperature anomalies of 1-2°C extending over a period of days to weeks should alert managers that a medium to high risk of bleaching exists.

DHW maps are updated every 3-5 days, allowing managers to track the development and persistence of temperature anomalies around coral reefs and to estimate bleaching risk. An automated email system sends managers Satellite Bleaching Alerts when stress levels are reached. All products are currently based on SST over a 50 x 50 km grid, and NOAA is improving this product to a grid size of 7 x 7 km. In many cases, the surface temperature measured by satellites can be used as a reliable indicator of the temperature of sub-surface waters (>1 m depth), depending on the extent of mixing. When anomalies are large or persistent, in-water instruments (described below) can complement regional satellite information and provide a more detailed account of local conditions.

The NOAA Coral Reef Watch program also developed a Tropical Ocean Coral Bleaching Indices web page to provide additional near-real-time information for 24 reef locations worldwide. For each reef site, the closest 50 km satellite data is extracted and listed on the indices web page. These data include: current SST, DHW, climatology, links to regional maps (such as ReefBase), SST time-series, satellite surface winds and retrospective data. Visual warnings are provided for each site when conditions reach levels known to trigger bleaching in vulnerable coral species.

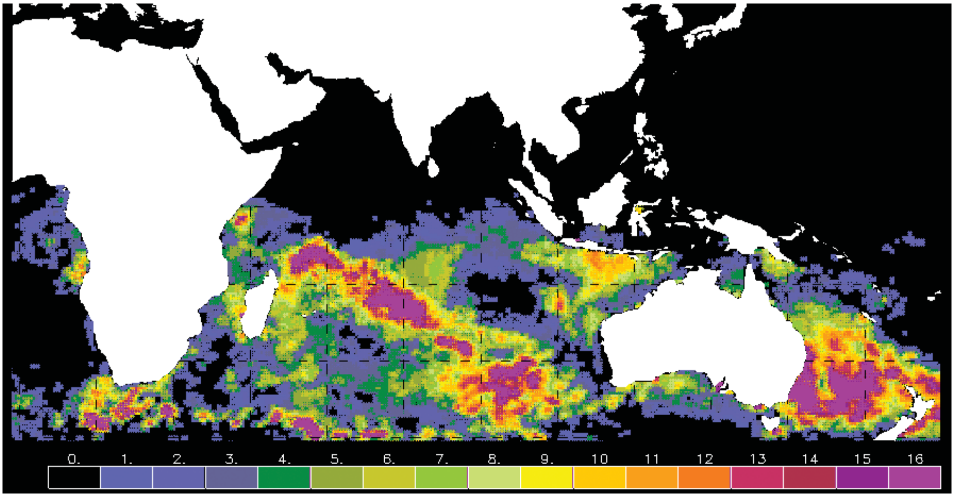

Figure 2.3 NOAA Degree heating weeks (DHW) map for the eastern hemisphere for 31 March 1998

Both the intensity and duration of heat stress are important factors in predicting mass coral bleaching, and the DHW maps combine this information into a composite unit of accumulated temperature stress over the last 12 weeks. One DHW is equivalent to one week of SSTs that are 1°C greater than the expected summertime maximum. At 4 DHW, conditions have become stressful for corals, and bleaching events become likely. Severe stress and possibly mortality is likely to occur at 8 DHW[50]. In this figure, the colours correspond to the number of DHWs indicated in the legend along the bottom of the map.

Direct measurements. Direct measurements of water temperature complement satellite imagery by providing data that are of higher spatial and temporal resolution. These measurements can be used to ground-truth remotely sensed surface temperatures. They can also provide measurements at multiple depths to establish a depth-temperature profile. Particularly for small reef areas with complex oceanography and strong mixing gradients, in situ measurements can help refine bleaching thresholds.

Local sea temperatures can be monitored using in situ instruments that either require manual download or are equipped with remote data transfer features. Simple, stand-alone temperature data loggers are now readily available and affordable. Data from several popular brands can be quickly and easily downloaded in-water by a diver. Where resources are available, weather stations with telemetry systems can be used to provide real-time data on a full range of variables that influence bleaching, such as air and water temperature, wind, current and irradiance.

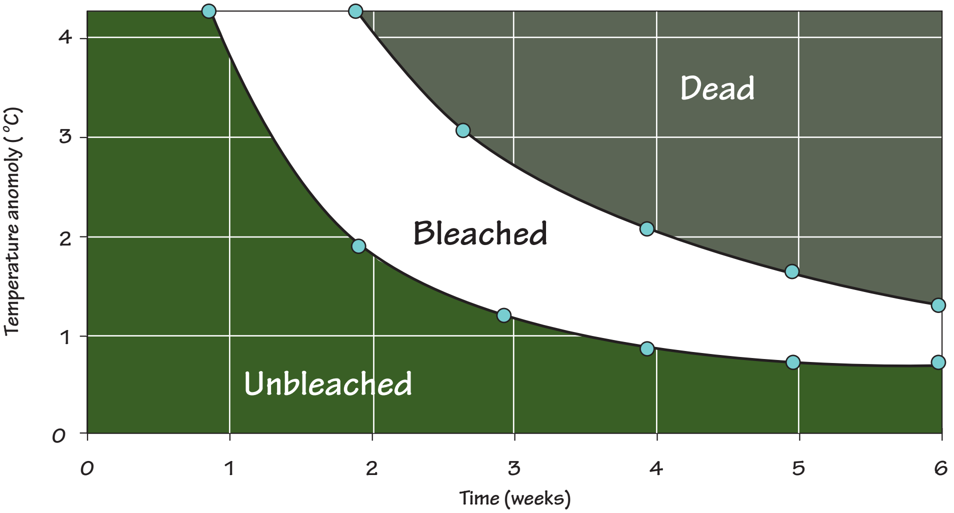

Figure 2.4 The relationship between the intensity and duration of heat stress and the risk and severity of mass bleaching

Directly measuring water temperatures can provide a more detailed account of local conditions to complement regional satellite information about temperature anomalies and bleaching risk. Predicting bleaching risk from in-water measurements requires an understanding of the exposure likely to trigger bleaching in the local area. This graph shows the general relationship between the size of the heat stress (vertical axis), how long it lasts (horizontal axis) and the onset of bleaching. Actual bleaching thresholds will vary by location based on typical ambient conditions and the sensitivity of the dominant coral reef species present.

2.2.3 Coral bleaching thresholds: how warm is too warm?

Interpreting bleaching risk based on direct measurements of sea temperature requires an understanding of the exposure likely to trigger bleaching responses. As introduced in Chapter 2.2.2, the risk and severity of mass bleaching is directly related to both the intensity and duration of exposure to unusually warm sea temperatures. Figure 2.4 illustrates the concept of bleaching thresholds based on temperature and exposure time. This section describes three approaches that can be taken to identify mass bleaching triggers: average high temperatures, past bleaching events and experimental observations. Since the composition of coral communities change, colonies acclimatise and species adapt in response to repeated thermal stress events, triggers can drift over time for particular species or regions; thus, bleaching thresholds should be reviewed regularly and revised as necessary.

Thresholds based on average maximum temperatures. The simplest approach, and the one used to create NOAA's HotSpot and DHW maps, is to compare temperatures against the average maximum temperature in order to calculate a temperature anomaly. Observed temperatures should be compared against average high temperatures for the same month. For example, sea temperature measurements taken in July are compared against the average high temperatures observed in July over the previous ten or more years. Where a long history of local temperature records is not available, managers may be able to derive long-term averages from satellite data sets. These data sets may be available on the Internet, or can often be provided upon request by the coordinators of satellite-derived sea temperature data, such as NOAA, or the Australian Commonwealth Scientific and Industrial Research Organisation (CSIRO). Once managers know the long-term average temperatures, it is a relatively simple matter to record current temperatures (using a regularly checked logger or real-time weather station) and compare this with the long-term average. Anomalies should be calculated on a daily or weekly basis and summed to provide a measure of the accumulated exposure to temperatures above the normal maximum. This simple index gives the number of degree heating days or weeks (DHDs or DHWs) for a particular period. NOAA issues a bleaching warning for monitored areas once heat exposure is greater than four DHWs[50]. This indicates that stress levels are high, and managers should consider initiating rapid assessments of reef condition, or at least heightening awareness in a volunteer network used to detect the onset of bleaching (Section 2.3). Anomalies of 1-2°C for days to weeks can induce coral bleaching in many susceptible species, and should alert managers that medium to high risk of bleaching exists.

Thresholds based on past bleaching events. Estimating bleaching thresholds in this way requires reliable records of when coral bleaching did and did not occur in previous years at reefs within the area of interest. Bleaching records are then matched up with temperature records in order to compare the average maximum temperature of bleaching years with that of non-bleaching years. The bleaching threshold falls between the lowest temperature for bleaching years and the highest temperature for non-bleaching years, taking both the intensity and duration of exposure into account. Depending on the resolution of past observations, this analysis may be carried out at either regional or local scales. An example of a detailed estimation of local bleaching thresholds for Kelso Reef in the Great Barrier Reef, Australia[52] is described in Box 2.1. A regional-scale analysis of bleaching thresholds has also been completed for the Indian Ocean region[51].

Box 2.1 Estimating bleaching temperature thresholds for Kelso Reef, GBR, Australia

Experience on the Great Barrier Reef indicates that threshold curves of reefs with similar communities and species vary with latitude and, more precisely, with local ambient temperature regimes. This correlation suggests that reefs have adapted or acclimatised to local conditions and reinforces the need for locally specific bleaching thresholds for use in an early warning system. Such time-temperature bleaching threshold curves are not species-specific, but, if field observations are based on early signs of bleaching, are usefully biased towards the sensitive members of the coral community.

In this example for Kelso Reef (Figure 2.5), cumulative exposure times and temperatures are shown for four consecutive years, one of which coincided with mild bleaching (1998). This graph shows the period when the warmest average daily temperatures were recorded (December to March). Average daily temperatures near the maximum summer range were summed to produce a cumulative frequency distribution of days and temperatures at increments of 0.1°C. The shaded area between the 1998 curve and that for the warmest non-bleaching year (1999) indicates the potential area in time-temperature space in which bleaching could occur. The predicted bleaching curve (bold solid line) was estimated by weighting the mean on a four-point scale according to the intensity of bleaching[52].

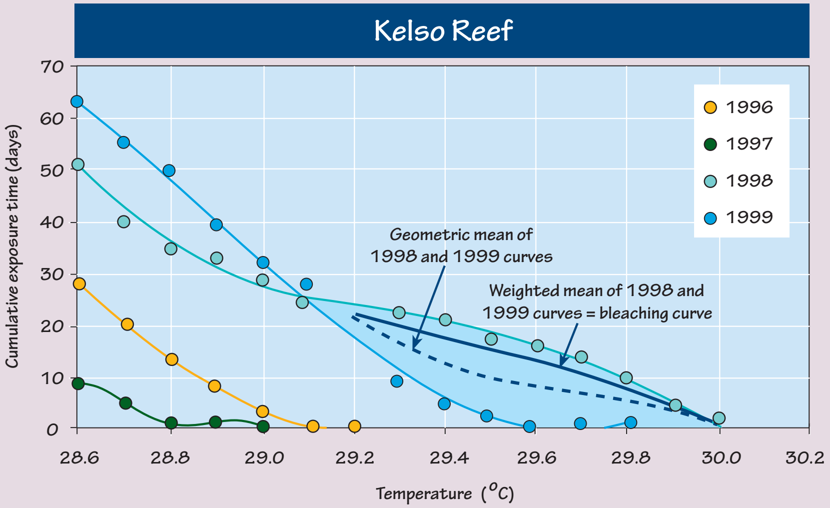

Figure 2.5 Bleaching thresholds for Kelso Reef in the central Great Barrier Reef, Australia

Coral bleaching thresholds can be calculated on the basis of temperature records and observations about the onset and severity of bleaching over several years. The shaded area in this graph shows the predicted bleaching threshold as the cumulative exposure falling between the coolest bleaching year (1998) and the warmest non-bleaching year (1999). From Berkelmans (2002)[52].

Thresholds based on experimental data. This approach is the most resource intensive and will likely require collaboration with scientists to collect detailed experimental observations. The approach, developed by Coles and Jokiel[53] and applied more recently by Berkelmans[52] (See box 2.1), involves exposing corals to different water temperatures in a laboratory situation and recording how many days are required for corals to show visible signs of bleaching at each temperature. Time-temperature bleaching threshold curves derived in this manner can provide the basis for detailed predictions about when bleaching may become evident in select species from particular locations. Care should be taken in applying data obtained from these observations to other species or locations. If the species selected for study are common, relatively sensitive, and from locations that are representative of the wider area, the thresholds can be useful predictors of bleaching within larger jurisdictions.

2.3 Assessing ecological impacts

Managers must rapidly assess the extent and severity of mass bleaching in order to make timely and effective management decisions (Section 2.5) and communicate the situation to others (Section 2.6). Reef users, other stakeholders, the media, and senior government officials will want to know: '*How bad is it? What are the impacts to the reef?*' and '*What will it mean for the local stakeholder community?*'. Thus, we now turn to a discussion of approaches for assessing the ecological (Section 2.3) and socioeconomic (Section 2.4) consequences of mass bleaching events for coral reefs and for the stakeholders who value the ecosystem services those coral reefs provide.

Coral reef monitoring protocols have been developed for a wide range of skill levels, ranging from Reef Check for volunteers to the comprehensive *Survey Manual for Tropical Marine Resources* developed by the Australian Institute of Marine Science (AIMS) and the Global Coral Reef Monitoring Network[54] for reef scientists and managers. Since mass bleaching is transitory in nature, the decision about when to conduct a rapid assessment of bleaching impacts and which protocol to use may have significant implications for the survey results and for any conclusions made from those results.

Experience from around the world during previous bleaching events has led to the development of strategies that can help with such timing concerns and other monitoring-related decisions. The WWF, the WorldFish Centre and the Great Barrier Reef Marine Park Authority (GBRMPA) have compiled these experiences into *A Global Protocol for Assessment and Monitoring of Coral Bleaching*[55]. The protocol can be downloaded from the ReefBase website (www.reefbase.org) by searching the online literature database, or by contacting the authors. The protocol aims to provide detailed guidance for planning and implementing bleaching assessments under a range of resource settings, while ensuring that data are useful and readily integrated into a global database of coral bleaching impacts.

Designing and implementing a coral bleaching monitoring program – Bali Barat National Park

© Naneng Setiasih

Bali Barat Monitoring Team

Coral reefs of Bali Barat National Park

Bali Barat National Park contains the most significant area of coral reefs in Bali, and is a focal point for reef conservation in Indonesia. It is a major destination for reef-oriented tourism and contains the only reefs in the region that are under formal protection. Nevertheless, these reefs are at risk from a variety of human activities such as (illegal) destructive fishing, nutrient inputs and anchor damage, and the threat of coral bleaching. The area suffered a crown-of-thorns starfish *(Acanthaster plancii)*, or COTS, outbreak in 1996-97 and was affected by mass coral bleaching in 1997-98.

The role of WWF

The WWF is the lead partner in efforts to study, manage and protect the coral reefs of Bali Barat National Park. The damage observed by the WWF during the 1997-98 coral bleaching event lead to renewed concerns about the sustainability of these reefs under existing management regimes. In particular, the WWF was concerned that the added pressure of climate change would make the reefs particularly vulnerable to existing levels of dynamite fishing, water pollution and poor anchoring practices.

In response to these concerns, the WWF collaborated with experts from the Great Barrier Reef Marine Park Authority (GBRMPA) and the International Centre for Living Aquatic Resources Management (ICLARM) (now WorldFish Centre) to develop a coral bleaching monitoring program for Bali Barat National Park. The resulting program was designed to detect coral bleaching and assess the extent and implications of any bleaching events, yet be implemented with minimal resources. Furthermore, in order to evaluate the importance of various factors in conferring resilience to coral bleaching, the program aimed to monitor the condition of local reefs from 2003 to 2006. The information from this program will be used to assess and improve the effectiveness of management strategies to mitigate bleaching-induced impacts and to protect coral reefs in the area, as well as to raise awareness about coral bleaching and climate change.

The Coral Bleaching Monitoring Program

This WWF Monitoring Program was designed to use existing staff expertise and resources, and to require only modest on-going funding. The WWF uses web-sourced El Niño predictions and NOAA HotSpot maps to assess the risk of bleaching each season. These remote data are backed up with measurements of local temperature obtained using low-cost temperature loggers that are installed at key sites and downloaded regularly (ideally weekly during the bleaching season) by WWF staff or their colleagues in the local tourism industry.

The WWF has also established a network of reef users to provide an early warning system for bleaching or other indications of stress on the reef. This program, called KEYS, 'Keep your Eyes on the Reef', encourages professional and recreational reef users to report any observations of coral bleaching at the sites they frequent.

Reports of possible bleaching received through the KEYS program trigger a field check by the WWF Bali coral reef team. This team consists of staff with appropriate SCUBA diving skills and a mix of scientific training, ranging from Masters Degree to no formal university degree. The team was trained in coral bleaching assessment skills during a four-day workshop run by external experts. The team leader runs regular refresher and calibration sessions to ensure skills are maintained within the team. The WWF team works closely with local tourism and fishing businesses in the area, receiving assistance from local reef guides, and cost-effective access to dive boats and equipment.


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Monitoring on the reef slope at Bali Barat National Park

If field checks indicate that a bleaching event is occurring, WWF launches a full bleaching assessment survey. This entails a rapid survey of all sites, using timed swims to determine the general severity and extent of bleaching within the Park and surrounding areas. This is followed by detailed monitoring of core sites, using the line intercept technique (LIT), permanent quadrats and a complementary study of tagged colonies. These methods have been chosen because of their widespread use, standardisation and, consequently, ease of comparison of results with other reef regions. Importantly, they can be implemented without the need for expensive equipment or high levels of expertise. Detailed monitoring is done regularly on a semi-annual basis as part of a four-year program designed to provide essential baseline data to document the longer trends in reef condition within the Bali Barat National Park, and to help understand the importance of coral bleaching relative to other threats affecting the area.

So far, WWF Bali has completed three baseline monitoring surveys (in February and October 2003, and March 2004). There was no bleaching event recorded during those times. The data indicate a trend that implies coral cover is recovering after the impacts of COTS and coral bleaching during the period 1996-98.

Establishing a network of coral bleaching monitoring programs. Parallel programs are being developed to assess the socio-economic impacts of coral bleaching and mortality, and to identify and promote strategies to mitigate the socio-economic impacts arising from coral bleaching events.

The Bali Barat National Park Coral Bleaching Program is one element of an integrated program being developed by the WWF. The program is designed to understand, document and mitigate climate change impacts on coral reefs worldwide. A network of areas with similar programs is being established and will include Bunaken National Park (Indonesia), American Samoa (USA), Batangas (the Philippines) and Tubataha Marine Park (the Philippines). Linkages with additional areas are also being explored, including with Ujung Kulon National Park (Indonesia), Cendrawasih Marine Park (Indonesia) and the Great Barrier Reef Marine Park (Australia).

For more information about the Bali Barat National Park Coral Bleaching Program, and related regional initiatives, contact:

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CASE STUDY 2

Community participation in monitoring coral bleaching events on the Great Barrier Reef – BleachWatch

The Great Barrier Reef Marine Park has experienced two major coral bleaching events in recent years (1998 and 2002). These have dramatically increased awareness of the threat posed by coral bleaching to the Great Barrier Reef ecosystem. Increasingly, reef users, the general public, the media and senior decision-makers are looking to reef managers to provide timely and credible information about the impacts and implications of coral bleaching.

However, resource limitations in conjunction with the size and remoteness of many reef areas can be a substantial challenge for reef managers wishing to detect the onset of bleaching and monitor bleaching-related impacts. Reef users can play an important role in assisting managers to keep an eye on the reef during periods of high bleaching risk. In the Great Barrier Reef region, a program to facilitate active community involvement in monitoring coral bleaching events has been created. This program, called 'BleachWatch', provides an early warning system for coral bleaching and forms part of the Great Barrier Reef Marine Park Authority's (GBRMPA's) Coral Bleaching Response Plan.

The BleachWatch program acts as an important source of information for managers, and also has an important outreach and communication function. Two different programs, 'BleachWatch-Professional' and 'BleachWatch-Community' have been developed to engage the range of reef users.

BleachWatch participants are provided with a Monitoring Kit. The kit includes a neoprene wrist band to assist with coral identification, a laminated reference sheet, survey form and instructions

The BleachWatch-Professional program is designed for regular reef users, predominantly tourism professionals or marine park rangers who visit a particular reef on a regular schedule. This program is an opportunity for marine tourism professionals to establish an understanding of the coral community at their sites, with the assistance of coral reef ecologists at the GBRMPA. A short monitoring form, which takes about 10 minutes to complete, is provided to participants. Monitoring kits, provided by the GBRMPA, also comprise a waterproof reference key and instructions. The program has been designed with the tourism professional in mind, and allows monitors to go about their everyday work, be it guiding snorkel trails or diving, while taking a mental picture of their 'home reef' with the help of the waterproof reference key. Once back on the vessel, staff members fill in the monitoring form and send it back to the GBRMPA at no postage cost. In return for the monitors' efforts, the GBRMPA analyses the information and provides monthly site reports, collating the data into an informative poster that can be displayed for the education of both staff and tourists.

The BleachWatch-Community program is designed for incidental observations made by reef visitors who make only occasional trips to the reef. Tourists, students and scientists can all contribute to this program by submitting reports via the GBRMPA website. A printer-friendly form is also available to help visitors record observations while they are visiting the reef. Reef visitors are encouraged to submit their data using the online form, and are reminded that a report of no bleaching can be just as important as a report of bleaching.

Information collected through the monitoring form includes:

(a) weather information (wind speed, cloud cover, water temperature)
(b) site information (reef name, type of reef habitat, depth surveyed)
(c) coral cover and community composition (such as dominant coral types)
(d) bleaching information (percentage of coral affected, severity of bleaching, types of growth forms affected).

Participants in both programs are encouraged to report observations prior to and during a coral bleaching event, so that the condition of the reef can be determined and monitored over time. This information provides an important early warning system for managers, indicating where coral bleaching is occurring and how severe it is. The BleachWatch program has been extremely successful in enabling community members to participate in monitoring the Great Barrier Reef and to improve their knowledge about coral bleaching, and reef ecology in general. Reef managers benefit by gaining an early warning of coral bleaching.

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Bleaching impacts may be assessed by way of: (1) volunteer and community-based reports, (2) broad scale assessments and (3) site assessments (Table 2.3). These approaches involve different techniques of data collection by different types of teams with different levels of detail and expertise required. Each approach has advantages and disadvantages in terms of cost, ease of mobilisation, and training required; yet each approach yields information of interest to managers and stakeholders. The choice of assessment approach will depend on the nature of the management questions posed, the nature of the manpower available to do the work, the amount of resources available, and the type of data needed for analysis. A brief overview of the three types of approaches follows. Table 2.3 briefly describes a variety of techniques used in the three approaches and provides a summary for each of the management questions they address, the pros and cons of each technique, and the nature of the data that they provide. An example of how these techniques have been combined into a coral bleaching monitoring program for Bali Barat National Park in Indonesia is described in case study 1. For more in-depth information on how to use these techniques, the reader is directed to *A Global Protocol for Assessment and Monitoring of Coral Bleaching*[55].

2.3.1 Techniques for bleaching assessment

Volunteer and community-based reports. In many cases, stakeholders come into more frequent contact with the reef than do managers. A key goal of a volunteer monitoring program is to take advantage of these 'extra eyes and ears' to rapidly detect the onset of bleaching and support timely management decisions. Another benefit is the opportunity provided by such programs to inform stakeholders about the impacts of mass bleaching and to engage them in coral reef management issues. Often, people feel helpless during mass bleaching events. Volunteer monitoring programs provide a means for community members to help by acting as reef stewards, thereby heightening public awareness of bleaching impacts and of climate change in general. An example of a volunteer bleaching program is the GBRMPA's BleachWatch program, described in case study 2.

Key elements of a community-based bleaching monitoring program are:

- establishing and maintaining a network of reef users to provide casual and regular reports of bleaching status at reef sites.
- developing and distributing an appropriate assessment protocol and datasheets for participating reef users to use to report reef conditions and coral bleaching.
- encouraging regular reporting of both bleaching and non-bleaching observations.
- providing regular and useful feedback to volunteers about their data.

Table 2.3 Management questions and ecological assessment techniques

Technique	Description	Advantages/ disadvantages	Data collected
Volunteer and community-based reports			
• Is bleaching occurring? • Where is it occurring? • What proportion and types of corals are affected, and how badly?			
Monitoring by volunteers	• A network of volunteers is established to report on conditions at their sites and assess whether or not and to what extent bleaching is occurring. Volunteers might include tourism operators, community members, students, NGO staff, scientists or enforcement officers. • The University of Queensland has developed a colour chart system to help volunteers*.	• Cost-effective method for determining if bleaching is occurring and the extent of bleaching, potentially over a large area. • Depending on volunteer training, data may be quite subjective.	• Presence/absence of bleaching at one or multiple sites. • Indication of bleaching progress and severity.
Broad-scale assessments			
• What is the total area (of a large reef ecosystem) affected by bleaching? • How severe is the bleaching?			
Timed swims	• Observers swim in a straight line or 'wandering' path within the depth range selected. Swims are broken into fixed time units, (i.e. 2 minutes). • An example of the use of timed swims to assess bleaching is found in McClanahan et al (2001)[56]. • Table 2.4 provides a simple index for rapidly estimating the proportion of colonies affected.	• Requires expertise to identify corals to at least the genus level. • Capacity to be performed in remote locations. • Does not require access to aircraft or landing strips. • Provides greater resolution of reef characteristics than do aerial surveys. • Useful for selecting representative sites for more detailed surveys • Suitable for detailed coverage of smaller areas or for sparse. sampling of larger areas • More time spent diving and associated costs.	• Percentage of live coral cover. • Dominant coral types. • Percentage of coral bleached. • Average severity of bleaching.

Table 2.3 (cont)

Technique	Description	Advantages/ disadvantages	Data collected
Broad-scale assessments (cont)			
Manta tows	• An observer is towed behind a boat at a slow and constant speed. Tows are broken into fixed time intervals, usually 2 minutes, during which time observations are made. • Most suitable for reef areas between 10-100 km^2. • Detailed guidance is provided in English et al (1997)[54] methods developed for surveying COTS are applicable. • Table 2.4 provides a simple index for rapidly estimating the proportion of colonies affected.	As for timed swims, but: • Allows efficient coverage of larger areas. • Requires boat and manta tow equipment (can be made inexpensively). • Limits opportunities for detailed inspections. • Not suitable for reefs in deep or low-visibility locations.	• Percentage of live coral cover. • Dominant coral types. • Amount of coral bleached. • Average severity of bleaching.
Aerial surveys	• Observers fly in planes over large reef areas to determine if bleaching is occurring and to assess bleaching extent and severity. Data are collected by visual observation or by aerial photography. • To be reliable, conditions must include: 1. Coral cover >10 per cent. 2. Clear shallow water over reefs; low tide is best. 3. Good visibility; no high clouds or rain. 4. Wind <15 knots. • Flying height is determined by data collection method; low altitudes are preferred for visual observations (ie 500 ft) and higher altitudes (2000–10 000 ft) for photography.	• Particularly useful for assessing bleaching over large or remote areas of 100s to 1000s of km. • Require specific conditions of reef cover and visibility. • May substantially underestimate the impacts of bleaching. • Requires funds and availability of suitable aircraft.	• Percentage area bleached or proportion of reef sites bleached. • Estimates of proportion of corals bleached and severity of bleaching.

Table 2.3 (cont)

Technique	Description	Advantages/ disadvantages	Data collected
Site assessments			
• What are the local impacts of a mass bleaching event? • What percentage of corals have survived or died from bleaching? • What kinds of corals were most affected by bleaching? • Has the species composition or diversity of a reef changed due to a bleaching event?			
Line intercept transects (LIT)	• The observer swims along a transect recording the transect distance at every point where the type of organism or substrate changes, and the level of bleaching for each. • Table 2.4 provides a simple index for categorising the severity of bleaching. • Various schemes for classifying reef organisms have been developed for different levels of expertise.	• Widely used for assessing benthic reef communities. • Reliable and efficient. • Allows observers with limited experience to collect useful information, although some training in coral identification required. • Requires little equipment. • Is limited to addressing questions about relative abundance (cannot determine number of organisms or proportion of organisms bleached).	• Relative abundance of organism groups. • Proportion of cover bleached and severity of bleaching.
Belt transects	• Transect tapes are laid as in the LIT method; the observer records the identity and severity of bleaching of every sessile invertebrate within a set distance on both sides of the transect tape. The width of a belt transect is normally 0.5 m or 1 m. • Table 2.4 provides a simple index for categorising the severity of bleaching. • Various classification schemes have been developed for different levels of expertise.	• Reliable. • Does not necessarily require experienced observers, although some training in coral identification required. • Requires little equipment and is relatively simple. • Particularly useful for assessing the proportion of coral colonies that are affected by bleaching. • Less suitable than LIT for collecting data on relative abundance, and more time-consuming.	• Type, abundance and density of individual organisms. • Proportion of corals bleached and severity of bleaching.
Video transects	• A diver swims along the reef above a tape measure, recording on an underwater video camera the reef community. The video footage is analysed back in the laboratory. • The footage analysis should identify all bleached organisms and the severity of the bleaching responses (Table 2.4).	• Provides a permanent visual record of the reef community, and reduces time required in the field. • Requires relatively expensive equipment, trained analysts to collect the data, operate the video-analysis equipment and software, and interpret the footage.	• Percentage cover of organism groups. • Proportion of cover bleached and severity of bleaching. • Recovery rates. • Nature of shifts in species composition.

A variety of coral monitoring methods are presented and statistically evaluated for their effectiveness in reference Brown et al (2004)[57]

* More information on the University of Queensland Colour Charts is available at: www.coralwatch.org

Timed swims, manta tows and aerial surveys are techniques that help managers get a general sense of the extent and severity of a mass bleaching event

Broad-scale assessment. When designing a program to assess a mass coral bleaching event, managers will want to begin with an overall picture of the situation. Timed swims, manta tows, and aerial surveys are techniques that help managers get a general sense of the spatial extent and severity of a mass bleaching event. The most appropriate technique will depend on the size of the area that a manager wishes to survey. In-water techniques are relatively inexpensive and can provide detailed information about conditions on the reef including: assessment of the proportion of live coral cover and bare substrate, proportion of corals affected by bleaching, types of corals bleached, and both the severity of bleaching and amount of recently dead coral. They can also be useful for identifying sites representative of larger areas of reef. These are often the most useful locations for more detailed ecological surveys of coral bleaching impacts.

However, in cases of very large or remote coral reef areas aerial surveys may be the best option for conducting assessments in the relatively short time window available to assess the impacts of a coral bleaching event (typically 1-2 months after peak temperatures). In very large reef areas such as the Great Barrier Reef Marine Park, which spans 350 000 km^2, aerial surveys are the only feasible method for assessing the full spatial extent of bleaching. While aerial surveys have distinct advantages in such circumstances, the observations made should be interpreted with caution.

Aerial surveys of mass coral bleaching events can be the best option for conducting broad scale assessments in very large or remote coral reef areas

Points to consider when using aerial surveys include:

- Aerial surveys will be most effective in locations where reefs have high live coral cover and bleaching is moderate to severe.
- Aerial surveys of bleaching extent will be most accurate for shallow (5-10 m) reef communities on horizontal surfaces.
- Results of aerial surveys should be interpreted with the understanding that they do not distinguish reefs that have low coral cover from reefs on which corals have already suffered major mortality due to bleaching.

One way to address the above issues is to conduct site assessments at key selected locations in order to 'ground-truth' the interpretations that may emerge from aerial survey data. The next section discusses site assessments.

Site assessment. Site assessments help managers understand not just the extent and severity of mass bleaching, but also its impacts on the reef. These more detailed assessments are used to ground-truth broad-scale assessments of bleaching severity, and to provide a more thorough understanding of bleaching response patterns and any observable long-term impacts of the event. Specifically, they enable managers to directly assess the extent to which corals are recovering or dying because of the bleaching event.

Line intercept transects (LIT), belt transects and video transects are common methods for conducting detailed site assessments – these can help managers interpret broad-scale surveys and understand the impacts of bleaching on the reef

Ideally, site assessments are conducted before and after bleaching events so that the results of these surveys can be compared; however, this is not always possible. Whenever site assessments can be repeated 6-8 months after the bleaching event, and in subsequent years, they can provide answers to questions about how the bleaching event has affected the reef ecosystem, such as:

- Did bleaching result in changes to the species composition on the reef?
- Are corals differing in the rate of bleaching or the rate at which they either die or regain their zooxanthellae?
- Overall, how quickly is the reef recovering?

Line intercept transects (LIT), belt transects, and video transects are common methods for conducting detailed site assessments. In all three methods, tape measures are laid out along the reef to provide replicate transects. Deciding where to position transects is important. Survey sites should be partitioned into two or more depth zones (for example the upper reef slope and lower reef slope), and transects laid randomly within the depth ranges specified. Therefore, in many cases transects will be positioned parallel to the reef crest. The length and number of replicate transects should ideally be decided based on pilot studies that assess the level of variation in the reef community in the survey area. Often, however, time and resources do not permit pilot studies. In these cases, a general rule of thumb is to use 20 m long transects, with a minimum of three (ideally five or more) for each depth zone at each site. More patchy or variable reef communities will require longer or more transects. Another way of minimising the effect of high variability in a reef community is to use permanent transects. These are marked out on the seabed with metal stakes or rods, so that the tape measure can be placed in the same location during subsequent surveys. Advances in GPS technology make returning to the sites relatively easy. More detailed guidance on the use of transects to survey coral reef communities can be found in the references[54, 55, 57].


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A diver completes a rapid survey of bleaching in Bali Barat National Park (Indonesia) as part of an ongoing coral bleaching monitoring program described in case study 1

Observers record different information for each of the three techniques. When using LITs, the observer notes changes from one benthic life form (plant or animal growing attached to the seabed) to another along the transect. In contrast, when using belt transects, the observer records every organism within a set distance on either side of the transect, usually 0.5-1.0 m. Though more time intensive, belt transects cover a greater area of the site than LITs can. Therefore, managers choosing to implement this method can better assess the proportion of coral colonies that are affected by bleaching and can evaluate differences in bleaching response that may be linked to colony size.

When using video transects, a diver uses an underwater video camera to film the reef community either along a measuring tape or using a standardized swim time. The video footage is analysed back in a laboratory. This approach can also be achieved using a still camera (digital or film), which can reduce the expense associated with video equipment. Still camera or video footage has the advantage of providing a permanent record of the bleaching event and potentially allowing for more accurate data analysis. However, both still camera and video data are costly, and the results are not available until after laboratory analysis is complete. Because information is needed quickly during a mass bleaching event, it is often useful to complement video footage with observations taken while in the water (for example by rapid in-water surveys[55]). This information becomes the basis for communicating the extent of bleaching impacts on affected reefs until the laboratory analysis is completed.

Data collected by LIT and belt transects can be tailored to the experience level of the observer

Data collection during LIT and belt transects can be tailored to the experience level of the observer. The benthic life forms are normally characterised using a broad taxonomic classification (such as class or family level) or morphological categories (for example branching, massive, etc.), or a combination of both. However, when the expertise of the observer permits, more detailed classification of organisms (to genus or species level) is preferred. Taxonomic detail allows for ease of comparison between reefs and reef regions during far-reaching events when bleaching impacts are being assessed by numerous agencies and researchers.

When applying any of these methods to a mass bleaching assessment, observers will also record the extent to which benthic life forms are bleached. While the focus of such surveys will usually be the hard and soft corals, observers should also record the bleaching category of any organism that appears to be bleached, such as clams, anemones or sponges. For results to be comparable between observers and locations, descriptions of bleaching severity should be based on widely used indices. *A Global Protocol for Assessment and Monitoring of Coral Bleaching*[55] recommends a simple index for categorising the severity of bleaching within reef organisms (Table 2.4), and for estimating the proportion of corals bleached within a survey site (Table 2.5).

Table 2.4 Recording the severity of bleaching of coral colonies

Category	Description
0	No bleaching evident
1	Partially bleached (surface/tips); or pale but not white
2	White
3	Bleached and partly dead
4	Recently dead

Table 2.5 Recording the proportion of corals affected by bleaching

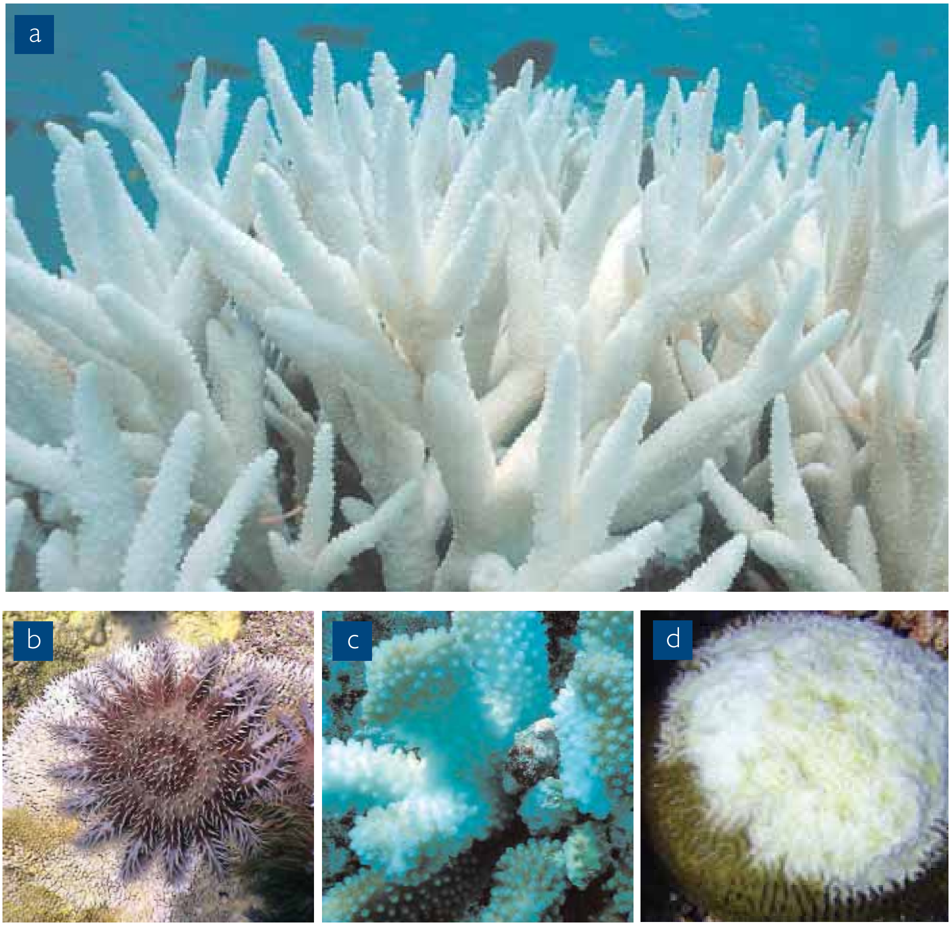
Category	Per cent	Description	Visual assessment
0	<1	No bleaching	No bleaching observed, or only very occasional, scattered bleached colonies (one or two per dive).
1	1–10	Low or mild bleaching	Conspicuous bleached colonies seen occasionally, but vast majority of colonies not bleached.
2	10–50	Moderate bleaching	Bleached colonies frequent but constitute less than half of all colonies.
3	50–90	High bleaching	Bleaching very frequent and conspicuous, most corals bleached.
4	>90	Extreme bleaching	Bleaching dominates the landscape, unbleached colonies not common. The whole reef looks white.

2.3.2 Special considerations for bleaching assessment

There are a number of considerations that a manager should be aware of when assessing mass bleaching events. The manager must be skilled at recognising when a mass bleaching event is occurring, deciding when to survey, and describing the severity of bleaching accurately. The following questions are helpful for providing guidance in these areas:

The proportion of corals affected and their spatial distribution normally distinguishes mass bleaching events from minor bleaching or other disturbances

How do I know whether what I am seeing is mass bleaching? Minor bleaching or paling of corals is a regular occurrence in many reef areas, and bleached colonies can be seen scattered throughout shallow coral communities during the peak of summer. More severe bleaching is sometimes seen within small reef areas due to localised stressors, such as flood plumes. Corals can also appear bleached when they are suffering the effects of coral disease or outbreaks of *Acanthaster plancii*, the crown-of-thorns starfish (COTS). It is important for reef managers to be able to distinguish between these various phenomena and recognise when an actual mass bleaching event is occurring.



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Mass coral bleaching is visually very distinctive, but determining whether bleaching or some other stress is affecting individual corals can sometimes be difficult. (a) Bleaching is usually distinguished by the way it affects entire colonies or large sections of colonies similarly. The effects of coral predators, such as (b) crown-of-thorns starfish and (c) drupella snails can often be recognised by patches of bare skeleton adjoining patches of live, healthy tissue. (d) Coral diseases can also be sometimes mistaken for the early stages of mass coral bleaching. Disease takes many forms, but the effects of disease are often characterised by a strong line separating live and dead parts of a coral, or by rapid erosion of the surface structure of the coral, as shown here.

Reef managers are often asked to distinguish between 'minor' and 'major' bleaching events. The proportion of corals affected and their spatial distribution normally distinguish mass bleaching events from localised bleaching. The early stages of a bleaching event may be limited to the bleaching of more susceptible species of corals and be confined to shallow reef areas. However, at the height of a mass bleaching event, large proportions of the coral community will be visibly affected. Obvious signs of bleaching will extend below the reef flat, to include the reef crest and slope, and will span sites throughout a region. Furthermore, the majority of corals will be at least pale (category 1 in Table 2.4), with many to most completely white (category 2). The proportions of bleached corals might be lower during a mild bleaching event or if the coral communities are dominated by more bleaching-resistant species. In these cases, managers can be confident that a mass bleaching event is occurring if signs of bleaching are being observed at reefs throughout the region. Rarely will the effects of a bleaching event be patchy within an otherwise uniform reef habitat, such as might occur when outbreaks of coral disease or coral predators (such as *COTS* or *Drupella*) move through a reef community.

The distinctions used by the GBRMPA (Table 2.6) to distinguish between minor, moderate and major bleaching events are based on general criteria that can be adapted to local needs and used when providing summary overviews of the severity of a bleaching event.

Table 2.6 Criteria used by the GBRMPA to distinguish between 'minor', 'moderate' and 'major' mass bleaching events

A 'minor' bleaching event shall be declared if there are:

- reliable reports of low coral bleaching (1–10% of colonies completely white) from multiple sites from multiple locations spanning at least two GBR sectors; **or**
- reliable reports of mild bleaching (10–50%) from a few sites only, scattered throughout the GBR or concentrated in only one sector.

A 'moderate' bleaching event shall be declared if there are:

- reliable reports of moderate coral bleaching (10–50% of colonies completely white) from multiple sites from multiple locations spanning at least two GBR sectors; **or**
- reliable reports of severe bleaching (>50%) from a few sites only, scattered throughout the GBR or concentrated in only one sector.

A 'major' bleaching event shall be declared if there are:

- reliable reports of severe to extreme bleaching (>50% of colonies completely white) from multiple sites spanning multiple sectors.

Ideally, bleaching surveys should be done at the peak of bleaching, when the bleaching is at its worst and before corals begin to die or regain their zooxanthallae

When is the best time to survey? Where managers have the resources to do 'pre-bleaching' (baseline) surveys, they should ideally be done just before the time of year when bleaching is most likely to occur. This works to minimise the chance that changes in the reef community due to other disturbances might be mistakenly attributed to a subsequent coral bleaching event.

The timing of 'during-bleaching' surveys is more difficult to determine. Ideally, bleaching surveys should be done at the peak of bleaching, when the bleaching is at its worst and before corals begin to die or regain their zooxanthellae. However, the timing and spatial pattern of mass coral bleaching can be highly variable from year to year. The onset of bleaching is influenced by numerous factors, including the extent and duration of temperature anomalies, variability in local oceanography, and variation in the types, abundance and distribution of corals. The most efficient and reliable means of determining if a bleaching event is actually occurring is via direct reports from people who regularly visit the reef. By monitoring both the levels of heat stress (Section 2.1) and the development of the bleaching event (via regular site visits or reports from reef users), managers should be able to estimate when bleaching is at its peak and implement bleaching surveys accordingly.

'Post-bleaching' surveys are ideally done once bleaching is fully resolved (that is, all corals have either recovered their normal colouration or died). In practice, for most situations, assessments of the level of mortality will be reasonably accurate if they are done between three and six months after the onset of bleaching. Post-bleaching surveys run the risk of underestimating levels of mortality if they are done too soon after bleaching is observed. If done too late, they can overestimate the impact of bleaching by including mortality caused by other sources.

How can I determine whether long-term changes on my reef are due to mass coral bleaching or other causes? Ongoing monitoring is required to document the long-term ecological impacts of coral bleaching and other major disturbances on reef ecosystems. It is necessary to track changes in reef communities over longer time frames (several years to decades) in order to estimate the probability and rate of recovery, increase the ability to determine the cause of changes in reef condition, and evaluate the effectiveness of management strategies. Maintenance of long-term monitoring programs will enable managers to detect gradual changes in coral community structure that may occur because of bleaching and mortality and to maximise their ability to attribute chronic impacts to particular stresses, including coral bleaching. Monitoring on an annual or semi-annual basis should be complemented with additional surveys timed to detect the occurrence and impact of coral bleaching at long-term monitoring sites. The data from such targeted surveys will help managers determine the relative influence of coral bleaching on the long-term dynamics of coral reef ecosystems.

Variable	Characteristic of bleaching event
Distance or area spanned by reefs that show signs of bleaching	Regional extent
Proportions of reefs or reef area that show signs of bleaching	Regional severity
Average proportions of coral colonies or coral cover that show signs of bleaching in area surveyed	Site severity
Average severity of bleaching of corals within area surveyed	
Relative resistance (based on hierachy of susceptibility Figure 4.1) of corals showing signs of bleaching	

Figure 2.6 Key variables for describing the extent and severity of a bleaching event

These five variables are useful in describing the extent and severity of a mass coral bleaching event and in describing the impacts of bleaching to a particular reef or site. Reporting these variables based on the widely used indices presented in Tables 2.4 and 2.5 is helpful for analysing and comparing different bleaching events.

2.4 Assessing social and economic impacts

The effects of mass bleaching events extend beyond their impacts on coral reef organisms. Coastal communities throughout the world's tropical regions depend on coral reefs for a range of ecosystem goods and services, including fishing, tourism, shoreline protection and recreation[35, 36, 58, 59]. Deterioration in the quality of coral reefs due to disturbances, such as coral bleaching, reduces the reef's ability to provide these commodities and opportunities, resulting in social and economic impacts. Importantly though, social and economic impacts can also arise from management strategies designed to sustain coral reef quality.

Reef managers, policy-makers and communities that understand the relationships people have with the adjacent coral reefs will be able to better identify both the impacts of a mass bleaching event and any impacts associated with management strategies. This knowledge can be used to design management strategies that maximise environmental outcomes while minimising negative impacts on people. Specifically, impact assessments can:

- identify the potential social and economic impacts of mass bleaching
- integrate local knowledge with technical expert knowledge
- evaluate the social and economic costs and benefits of various coral bleaching management strategies
- increase public involvement in the monitoring of bleaching impacts.

2.4.1 Socioeconomic impacts of mass coral bleaching

The nature and magnitude of social and economic impacts resulting from coral bleaching will be influenced by the level of dependency coastal communities have upon coral reefs. Economic impacts may take various forms, including decreased income, reduced business efficiency and decreased business confidence and investment. Social impacts of bleaching might include effects on people's lives (such as how they work, play, and interact), their culture (shared beliefs, customs, values and language) and their community (for example its cohesion, stability, character, facilities and services).

Coral bleaching events can have direct impacts on human uses of reefs by reducing the aesthetic qualities of reef sites that are important for tourism, and by decreasing the abundance or availability of fish stocks (an example of these impacts is described in case study 3). As a result, the major reef uses likely to suffer direct social and economic impacts from coral bleaching are tourism (diving, snorkelling, and charter) and fishing (commercial, recreational, indigenous and subsistence fisheries). An assessment of the economic impacts of mass coral bleaching in the Indian Ocean is described in case study 3.

Tourism impacts. The socioeconomic impacts of mass bleaching on tourism depend on the awareness level of tourists, the severity of coral reef degradation, and coastal community reliance on coral reef condition. Although the ecological impacts of coral bleaching can be both rapid and visual, many of the social and economic impacts can be subtle or gradual. For example, a study of tourists visiting the Philippines found that, generally, visitors had a low awareness of mass coral bleaching; the result being that these businesses did not experience any immediate losses as a result of a bleaching event[60]. Socioeconomic work in Palau found that during a mass bleaching event, the white or pastel colour of the coral improved the aesthetic appeal of dive and snorkelling sites for some tourists[61]. This highlights the fact that many tourists may be currently unaware of the negative ecological implications of bleached corals.


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Coral mortality resulting from bleaching events can have direct impacts on human uses of reefs by reducing the aesthetic qualities of reef sites that are important for tourism and by decreasing the abundance or availability of fish stocks. Degraded reef condition can also have more subtle social impacts on communities by affecting customs and values, and community cohesion or stability

Should coral bleaching lead to mortality, however, the declines in reef quality become very difficult to ignore. As a result, the satisfaction of divers and snorkellers visiting a site that is deteriorated because of coral bleaching is likely to decline, with possible implications for visitation rates, and consequent impacts on tourism businesses. Economic impacts on dive-oriented tourism have now been documented following coral reef damage caused during the 1997-98 bleaching event in Tanzania, the Maldives, Sri Lanka and the Philippines[62].

The socioeconomic impacts of mass bleaching on tourism depend on the awareness level of tourists, the severity of coral reef degradation, and the industry's reliance on coral reef condition. Some studies have shown tourists to be unaware during bleaching events or even to feel that the white or pastel colour of the corals improved the visual appeal of the site. Should bleaching lead to mortality, however, the declines in reef quality become very difficult to ignore and can impact the type and number of divers choosing to visit the site

In the long-term, the extent to which coastal communities depend on coral reef condition will determine whether declines in reef quality due to coral bleaching translate into economic impacts. In some situations, tourism businesses have shown resilience to changing conditions. For example, a combination of issues, including coral bleaching, over-fishing, and tourism-related damage were perceived to have decreased the quality of reefs in the Philippines, causing a decline in occupancy of local hotels by divers from 80 per cent to about 10 per cent over 15 years[60]. The tourism industry recovered partly through a shift from reef-oriented dive tourism to 'honeymooners'. This less reef-oriented market segment now forms over 50 per cent of the resort bookings in the area[60].

CASE STUDY 3

Economic analysis of coral bleaching in the Indian Ocean

The 1997-98 mass coral bleaching event had severe ecological consequences for Kenya, Tanzania, and the Seychelles, with each country estimated to have lost roughly 40-50 per cent coral cover. A two-phase study, undertaken as part of the Coral Reef Degradation in the Indian Ocean (CORDIO) project, estimated economic losses resulting from the mass bleaching event. Results suggest that, five years after the event, economic impacts are most noticeable in the tourism sector[38]. Results describing the economic impacts on fisheries incomes were inconclusive.

The study estimated tourism welfare losses by combining the results of a 'Willingness To Pay' (WTP) survey with estimates for coral recovery. The WTP survey found that tourists were willing to pay US$98.70 extra per holiday in the Seychelles, US$87.70 in Zanzibar and US$59.00 in Kenya in order to experience healthy coral reefs. Applying a conservative estimate that corals should recover at a linear rate over a 20-year period, and assuming that WTP relates linearly to recovery, the study estimated welfare losses in 2001 of US$9.7 million for the Seychelles, US$6.4 million for Mombasa, and US$5.4 million for Zanzibar. Net present values of these annual welfare losses over a 20-year time period with a 10 per cent discount rate shows considerable potential welfare losses: a total of US$71.5 million for the Seychelles, US$47.2 million for Mombasa, and US$39.9 million for Zanzibar.

Related studies showed that tourism losses could vary significantly between locations. A 2000 study by Cesar et al[34] found that, in the Maldives, tourism growth was cut by only one per cent as a result of coral mortality. This is despite significant declines in reef condition (live coral cover decreasing from 50 per cent to less than five per cent). The small loss in tourism is likely to be explained by the successful shift made by operators in the Maldives toward other types of tourism, 'honeymooners' in particular. In addition, with double-digit annual international growth in the number of certified divers, and the relative proximity of the Maldives to the European market, this archipelago is guaranteed a fresh supply of relatively inexperienced divers. New divers are mainly interested in large, charismatic marine creatures (large fish, sharks, turtles, etc.), which are readily visible in the Maldives due to low reef fishing pressure. By comparison, a 2000 study by Westmacott et al[12] found a 19 per cent drop in dive-related tourism to Zanzibar due to severe coral bleaching, corresponding to an estimated 10 per cent reduction in total tourism arrivals. The difference in measurable changes in tourism between the Maldives and Zanzibar is particularly interesting. One possible explanation is that the breadth of the tourism sector in the Maldives enabled a shift in tourism focus (from diving to beach-oriented holidays, for example) that minimised declines in total tourism revenue.

The impact of mass bleaching on fisheries in these nations was far less clear. While fish species' composition changed (in some cases considerably) overall yield and income for fishers did not change significantly. This suggests that fishers are targeting other species to compensate for bleaching-related declines in their normal target species. The influence of coral bleaching on overall fishery trends were difficult to identify because market price and fishing effort were being influenced simultaneously by other factors during the same period. For example, one study[150] found that catch per fisher decreased by around 25 per cent in Kenya in concert with estimated decreases in biomass on fished reefs. However, at around the same time as the bleaching event there was a 16 per cent increase in the number of fishers. Because these impacts coincided it was difficult to identify the reason for the decline in fish catches. Furthermore, despite an increase in the abundance of herbivorous rabbitfish on fished reefs following bleaching, the number of rabbitfish recorded in fishing catches declined due to changes in fishing pressure and target species.

These studies illustrate the difficulty in identifying the impacts of coral bleaching on fisheries. There are complex relationships between habitat quality, fish abundance, community composition and fishing pressure. Coral mortality resulting from bleaching can affect reef communities in two different ways. On one hand, coral mortality increases the opportunity for algae recruitment, which can lead to increases in primary productivity and consequently in the biomass of herbivorous fishes. However, coral mortality also leads to decreased habitat availability for fishes as waves, currents and bio-erosion reduce dead coral skeletons to rubble. This leads to reductions in fish diversity, and, for some species, dramatic declines in abundance[143]. From a fisheries perspective, the impacts of coral mortality associated with coral bleaching are likely to depend on the type of fishery, and the relative importance of increases in algal biomass versus decreases in habitat complexity for the resident fish community. However, fisheries, especially those characterised by small-scale operations, can be highly responsive to changing conditions, and shifts in fishing effort and species targeted can readily confound impacts of changes in abundance of fish populations related to coral bleaching events. More research is required to improve our understanding of the direct and indirect impacts of coral bleaching on fish communities, and on associated fisheries. Such information is essential for the development of management strategies that aim to sustain coral reef ecosystems and dependent fisheries in the face of future coral bleaching events.

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Fishing is an important use of coral reef resources, providing income and food to millions of people worldwide

Fishing impacts. Time lags can be expected between a coral bleaching event and associated social and economic impacts in fishing industries. Studies have documented changes in fish populations as a result of bleaching-related ecological degradation[63, 64]. However, studies have had difficulty demonstrating how changes in fish stocks have translated into changes in fishery yields or fishing income following coral bleaching events. In these cases, the adaptability of many fishers, and the confounding influences of other multiple influences on subsistence and commercial fishing have complicated efforts to understand the impact of bleaching on fisheries. For example, shifts to other target species, changes in net size, and the effects of market prices and other disturbances such as typhoons or upwelling events all serve to mask the possible effects of coral bleaching. However, deterioration in reef quality is likely to have lasting impacts on the sustainability of fishing pressures, even if they are not readily apparent. More comprehensive social and economic monitoring, with adequate baseline data, may be required to properly assess the impacts of coral bleaching events on fishing[38].

Indirect impacts. Coral bleaching may also have indirect effects on local and regional communities through their social and economic links to the fishing and tourism industries. Reduced prosperity of these industries can potentially lead to a multitude of flow-on effects to other elements of the community, ranging from local schools, accommodation providers and food stores, to hardware and fuel suppliers[65]. These subtle but important effects can have ramifications for the stability of regional and coastal communities.

Management strategies designed to protect reefs from coral bleaching may also indirectly affect people and industries by constraining the way people interact and access the reef. While unintended, these restrictions can have significant and lasting social and economic impacts. For example, management initiatives to protect herbivorous fishes from over-exploitation may substantially limit the ability of fishers to pursue their traditional target species. While some fishers in some regions may be in a position to compensate for such restrictions by switching to other species or even to other activities such as tourism, many may not. Understanding these effects will allow management initiatives to be more effective and equitable.

Social and economic resilience. Given the right circumstances, humans are able to adapt to a changing environment. Understanding what factors influence people's capacity to be resilient to change in quality or access to a natural resource is a key focus of current research[66]. Knowledge of a community's capacity to respond to change can strengthen management interventions and assist in predicting the longer-term social and economic impacts of coral bleaching. This adaptive capacity may vary significantly between developing island nations and developed countries with large land areas that vary in their dependency on coral reef ecosystems and in the diversity of their economies.

2.4.2 Measuring socioeconomic impacts from mass bleaching

Managers are likely to have a range of socioeconomic questions related to mass coral bleaching. Some of these are likely to be:

- What are the types of social and economic impacts likely to be experienced due to a bleaching event?
- Who is likely to be affected?
- What are the characteristics of people and industries potentially affected?
- What opportunities exist to minimise the direct effects of a bleaching event?
- How can management responses to bleaching be designed to minimise impacts on reef users?

Answers to these questions may help managers decide if, for example, a contingency fund for tourism operators should be established. Reef managers may wish to work with local communities to identify strategies to promote alternative business opportunities or facilitate access to other resources. Broader-ranging strategies, such as creating subsidies to change land-use practices, or strengthening regulations for land clearing, agriculture, and development may also be considered.

A framework for assessing bleaching impacts. Formal assessment of socioeconomic impacts can help managers to understand, predict and assess the impacts of change on individuals, families, communities and societies. In some instances, social and economic variables may already be monitored on a regular basis to assist with other aspects of reef management, and managers may wish to incorporate a bleaching element into these studies.

The science of measuring and understanding socioeconomic impacts has developed rapidly in recent years, and there are now guidelines for assessment programs. Properly implemented, socioeconomic impact assessments can be valuable tools in a reef manager's approach to minimising the impacts of coral bleaching events. While available resources may limit a manager's ability to complete comprehensive assessments, the impact assessment framework described in Box 2.2 can still provide important guidance for collecting relevant information.

This useful framework for socioeconomic impact assessments comprises six generic steps: scoping, profiling, prediction, evaluation, mitigation and monitoring[67]. Depending on the resources available and the goals of the assessment, not all steps may need to be completed to the same degree. If the main concern of the manager is to identify the main types of impacts, a scoping study may be adequate. In other contexts, it may be highly desirable to quantify all of the community-scale impacts, requiring the manager to complete each step of the assessment framework.

Assessing the character and significance of socioeconomic impacts resulting from mass bleaching can help managers communicate the importance of healthy coral reef ecosystems and develop strategies to minimize impacts on affected people and industries

Box 2.2 A social impact assessment framework

Formal socioeconomic impact assessments generally follow a six-step process. Each of these steps is described below in relation to coral bleaching. Familiarity with these steps can help managers identify realistic goals for social and economic impact assessments, and can provide guidance when developing collaborative assessment projects.

Scoping *involves identifying the goals, issues and methods for the assessment of the potential impacts that might be expected to result from mass bleaching events. The goals of the assessment will determine the social and economic variables that need to be collected. Wherever possible, a well-developed community involvement program should be integrated into the process. A scoping study conducted in consultation with the community may help identify goals important for the whole community with respect to coral bleaching. Community involvement not only provides important information for the development of the assessment, but also provides opportunities for the community to be informed about coral bleaching and involved in the management response. Suitable representatives from the local community, fishing industries (commercial, recreational and subsistence), tourism industries and traditional users should be engaged at this stage. Common methods for scoping include broad-scale workshops, industry-specific workshops, qualitative interviews, key informant surveys and desktop-analyses, or a combination of these.*

Profiling *describes the existing social and economic environment in which impacts are likely to occur. This step should identify the variables and indicators that describe the vulnerability or resilience of people and communities to bleaching events. Profiling provides baseline data about a community and can be carried out any time prior to a bleaching event. Such data provide bases for comparison should managers wish to set up a social and economic monitoring program to quantify the impacts of future bleaching events. Sectors of the community that should be profiled are normally identified in the scoping part of the study. Typically, profiling is achieved using standard survey techniques, although secondary sources such as census data may also be useful. A recent guide, SocMon[68], is an excellent reference to help with profiling surveys. An example of the use of profiling to characterise a commercial fishing industry prior to the implementation of various management actions is provided by a Guide to the Fishers of Queensland[65].*

Predicting *social impacts requires information collected during the profiling exercise to describe potential social and economic impacts. The probabilities, magnitude and distribution of impacts are also described in this section. Indirect impacts can be assessed by identifying and quantifying links between direct and indirect reef users. Prediction can also include quantification of the spatial links between the resource and reef users, and the subsequent economic and social links between users and the rest of the community. This information provides a basis for predicting the social and economic consequences of alternative management actions, such as various locations for 'no fishing zones'. Predictions may also be qualitative, with the results of the profiling exercise being assessed based on broad discussions with the community. Historical records may be important to access during this stage. Any prior change in the quality of the coral reef in the past–and any* *associated social and economic impacts that occurred–may be indicative of how a dependent community may respond to a bleaching event in the future. Historical records may also provide some information on the cumulative nature of social and economic impacts.*

Evaluation *is a process that determines the acceptability of potential impacts. This process should involve considerable public involvement since there are often significant differences between interest groups in how impacts are evaluated. For instance, reef managers may decide to implement a suite of Marine Protected Areas (MPAs) to assist reefs in their recovery from bleaching. The design and placement of the MPAs will have varying social and economic impacts, dependent on their location and size. The evaluation phase allows reef managers to assess the impacts associated with alternative proposals. This phase is initially conducted as a desktop study, but it is crucial to 'ground-truth' the results by querying those people likely to feel the impact. Transparency in evaluations is important if the community is to feel confident that impacts likely to affect them have been considered and understood.*

Mitigation *focuses on minimising impacts. The aim of this section is to develop management strategies that maximise the resilience of reefs, while minimising the social and economic impacts. Again, this step requires extensive community involvement in the design of strategies. Conflicts between user groups in their expectations for management concessions can be minimised with good community engagement.*

Monitoring *can enable reef managers to detect the onset of and changes in social and economic impacts associated with coral bleaching. In addition, a monitoring program will help detect unforeseen impacts, and assess whether mitigation strategies are working as intended. Reef managers may already have survey programs in place to address other goals of marine park management. Where there are existing programs, managers may wish to add components that can determine if the predicted impacts of coral bleaching events are occurring.*

Special considerations. While the structured approaches described here provide a solid framework for assessing bleaching impacts, managers should be aware of issues that impeded the progress of past impact assessments and discuss them with researchers when developing appropriate projects. As noted in the previous section, a key issue is separating the influence of mass bleaching from the effect of other disturbances and from other stressors. For example, studies estimating the economic impacts of the 1997-98 bleaching event on fisheries in the Indian Ocean region found that changes in fisheries effort and gear type made it difficult to isolate bleaching impacts given the data available. Similarly, several studies have found that significant decreases in tourism due to international terrorism attacks complicated attempts to identify changes in tourism associated with the degradation of coral reefs[37, 60, 69]. Challenges also arise when reef degradation results from

A key challenge in assessing the socioeconomic impacts of mass bleaching is separating out the influences of other stressors and changes in resource use – managers should discuss these issues with researchers during project design to focus studies in the most management-relevant directions

multiple sources. Coral reefs in Con Dao, Vietnam, experienced almost 100 per cent mortality in 1998 as a result of a typhoon followed by mass bleaching[15]. Because mortality resulted from the combined influence of both events, it is unclear how much of the subsequent socioeconomic impact should be attributed to the mass bleaching event. By discussing these issues during project design, managers will be able to extend the scope and limitations of research results, as well as fine-tune studies toward the most management-relevant directions.

2.5 Implementing management measures during bleaching events

The current section considers whether any meaningful actions can be taken during mass bleaching events to reduce negative ecological impacts. While above-average sea temperatures are outside the control of reef managers, other factors that influence coral reef resilience to mass bleaching events are amenable to management (also see Section 3.1.2). Ecosystem condition, which influences coral survivorship during mass bleaching events and reef recovery after bleaching-related mortality, can be maintained and improved by effective management of local stressors[40]. However, it is the physical conditions–temperature, light, and mixing–that principally determine whether corals bleach in the first instance. They also play a key role in determining the probability of mortality during bleaching events. While these factors are not amenable to intervention in conventional management approaches, concern about the future of coral reefs is driving new thinking about ways in which bleaching risk might be mitigated. The following strategies for management intervention are based on emerging ideas that mostly have yet to be tested. Some may turn out to be fruitful initiatives, especially those aimed at reducing local stressors; however, most should be considered experimental and undertaken in the spirit of adaptive management.

Bleached corals are in a state of extreme stress and therefore less resilient to local stressors, such as physical damage from recreation, degraded water quality, or pressure from fishing activities

2.5.1 Managing local stressors: recreation, water quality and fishing

Physical damage from snorkelling, diving and boat anchoring. The temperature anomalies that trigger coral bleaching events place substantial stress on coral colonies, even before there are any visible signs of bleaching[70]. Once a coral is bleached, it is in a state of extreme stress, with reduced capacity for feeding and maintenance of essential physiological functions, such as injury repair and resistance to pathogens[18, 23, 27, 71]. Snorkelling, diving, and boat anchoring are all activities that can cause physical injuries to corals if not carefully managed. A coral stressed due to bleaching is likely to be less capable of recovering from physical injuries due to these activities. Repair of even minor tissue damage may be hindered while the colony is in a stressed condition, increasing the risk of infection or overgrowth by competing organisms[71].

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Snorkelling, diving, and boat anchoring (shown here) are all activities that can cause physical injuries to corals if not carefully managed. A coral stressed due to bleaching is less capable of recovering from physical injuries due to these activities

Although the principles behind these theories are well established, there have not been any direct studies of the effect of bleaching on a coral's response to physical injury. However, reef managers may wish to explore the costs and benefits of minimising activities that could expose stressed corals to increased risk, especially in high-visitation tourism sites.

Water quality. Degraded water quality affects various life stages of corals[45, 72], making it likely that it exacerbates the effects of coral bleaching[42]. Acute increases in sediment and pollutants, associated with coastal development or dredging, deliver additional stress to corals that must clear sediment from colony surfaces, wasting precious physiological resources. Corals stressed from mass bleaching are likely to be less effective at defending against invasion by microalgae or at competing with macroalgae[71]. Additionally, nutrient inputs can significantly reduce coral recovery after bleaching-related mortality[45] (Section 4.2.3).

Short-term increases in sediment and pollutants associated with coastal development or dredging cause additional stress to corals that is likely to increase the effects of coral bleaching. Limiting particular coastal activities during bleaching events could reduce damage to coral communities, while also reducing the risk that the developer will be held responsible for any coral mortality that could be due to bleaching

In light of these implications, managers may wish to consider the timing of coastal activities during periods of increased temperature stress. Limiting particular coastal activities during bleaching events could reduce the risk of damage to coral communities that could result from negative interactions between stressors such as turbidity and temperature[41]. Such a strategy could also reduce the risk that developers will be held responsible for any coral mortality that could be due to bleaching.

Fishing activities. Herbivores play a critical role in facilitating recovery of coral reefs after major disturbances (see also Section 4.2.3). In many locations, the grazing activity of herbivores is essential to the maintenance of substrate suitable for coral recruitment[42, 45]. For this reason, should a bleaching event result in substantial coral mortality, a reef manager may wish to consider implementing short to medium term initiatives to protect the herbivore function that is necessary for the reef to recover. This is most relevant in underdeveloped countries where herbivorous fish populations are under threat from fishing pressure. These initiatives are most likely to be effective if they are done in partnership or consultation with relevant stakeholder groups. Ideally, restrictions would be maintained until significant recovery is evident or until there is other evidence that adequate settlement substrate can be maintained despite fishing pressures.

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Herbivores play a critical role in facilitating recovery of coral reefs after major bleaching events by maintaining suitable substrate for coral recruitment. Should a bleaching event result in substantial coral mortality, managers may wish to work with local communities to implement short- to medium-term initiatives that protect the herbivore function necessary for the reef to recover

2.5.2 Impeding the causes: light, temperature and mixing

Light. Ultraviolet light is known to be a key factor in coral bleaching[73], and small-scale experiments have shown that reducing intensities of UV light have reduced the incidence or severity of bleaching[24]. These observations suggest that shading moderate sized areas during periods of greatest temperature stress may reduce the amount or severity of bleaching. However, practical considerations involved in implementing a shading strategy, as well as the potential for unwanted side effects, make this proposal particularly challenging. Small to medium-scale experimental tests of this strategy would be best accomplished through close science-management partnerships.

Temperature. Although water temperatures are not amenable to management intervention at large spatial scales, there may be potential for temperatures to be manipulated in some localised circumstances. In situations where high water temperatures are due to the solar heating of shallow or contained water bodies, relatively small volumes of cool water may be adequate to maintain temperatures below critical bleaching thresholds for at least some species. Deep water adjacent to such sites may provide a readily available source of cool water. This strategy may become increasingly appealing at high use tourism sites should coral reefs continue to degrade because of temperature-induced stress. The feasibility of this idea has not been thoroughly investigated to date, and no field tests are known.

Mixing. The amount of water exchange around a coral colony during thermal stress has been hypothesised to influence the severity of bleaching[74]. Increased water flow is thought to increase the flushing of toxins that are the by-products of the cellular processes which lead to coral bleaching. Therefore, it is possible that increased flushing of toxins through greater water circulation around coral colonies may reduce the severity of bleaching or at least delay the onset of bleaching. If greater mixing could be achieved, it is likely that the amount of damage from a thermal stress event could be reduced. The role of water flow in determining the impacts of thermal stress on corals is still being studied, and the practicality of this concept as a strategy for management intervention has not yet been explored or tested.

It seems unlikely that interventions aimed at reducing temperature and light are practicable except at a very small spatial scale, such as at discreet, highly valued tourism sites

2.6 Communicating about mass bleaching

Mass coral bleaching is a visually spectacular phenomenon with potentially severe implications for the health of coral reef ecosystems, the enjoyment of visitors, and the prosperity of individuals and businesses that depend on the reef. For these reasons, bleaching is an issue that attracts strong interest from the public, the media, and policy/decision-makers. In response, managers will want to provide up-to-date and informative answers to important questions about mass bleaching events and related impacts. Preferably, managers will proactively engage their target audiences (Figure 2.7) in discussions about mass bleaching and the actions that are needed to build coral reef resilience.

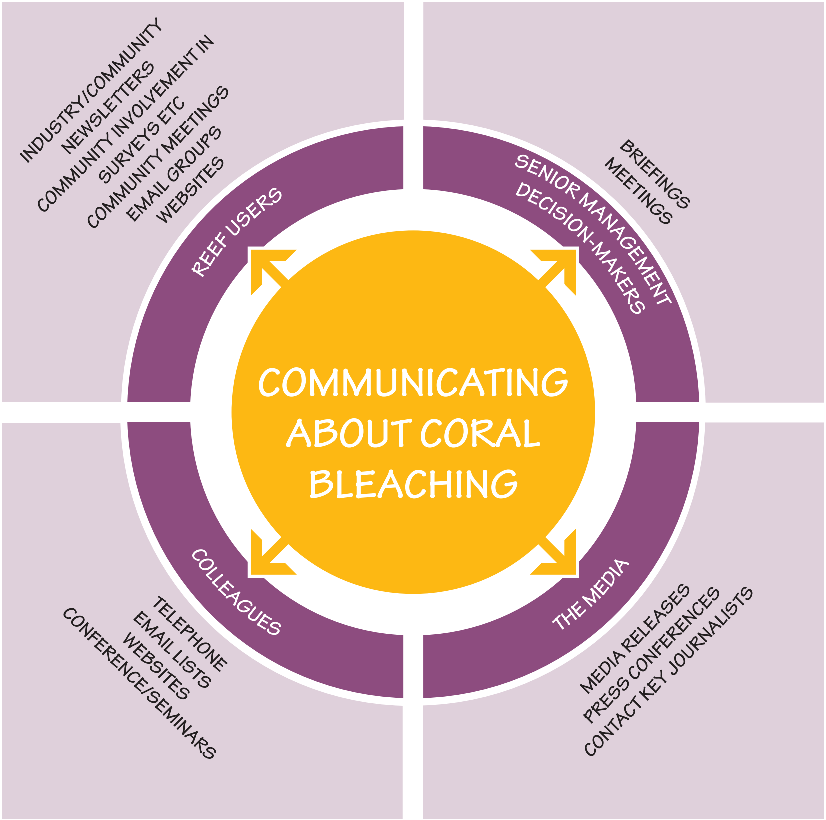

Figure 2.7 Target audiences and strategies for communicating about coral bleaching

Mass bleaching attracts strong interest from the media, reef users, senior decision-makers and management colleagues because it is visually spectacular and has potentially severe implications for the health of reef ecosystems. Effectively communicating with these audiences will increase support for coral reef management responses.

A communication strategy for responding to mass bleaching might have three aims:

(1) Gain support from supervisors and constituencies to respond to mass bleaching in the short and long term
(2) Engage stakeholders in a two-way communication about the extent and severity of bleaching and actions that can be taken to build reef resilience
(3) To work with the media to raise awareness of mass bleaching events and their impacts among the general public.

This section outlines strategies for working with target audiences–senior decision-makers, reef users, the media and colleagues–and provides examples of answers to common questions about mass bleaching events. It also identifies available resources for outreach and education.

2.6.1 Strategies

In working with any audience, managers are advised to take an approach that is clear and well thought out, proactive, solution-oriented, balanced, and respectful of political constraints. In communicating about mass bleaching, it is important that managers maintain the trust of their supervisors and the credibility of their reputation. Managers should be aware of political and social sensitivities and operate within organisational constraints. Managers also need to resist temptations to over-dramatise issues or events in order to meet the expectations of the press. This is of particular importance when bleaching is patchy and tourism operators are wary of the condition of their frequently visited sites becoming highlighted in the media. Lost credibility due to exaggeration of facts or presentation of premature conclusions can be costly and, sometimes, impossible to regain.

In working with any audience, managers are advised to take an approach that is thought-out, proactive, solution-oriented, balanced, and respectful of political constraints

Whether made up of supervisors, stakeholders, or the media, audiences are likely to be more receptive when they feel they are being consulted early and presented with options or useful information. When people feel attacked or helpless to solve a problem, they may become frustrated or angry, disengage in the discussion, or actively try to cover-up the issue. For this reason, over-dramatisation and focus on negative scenarios can be destructive to efforts to address the threat presented by coral bleaching. Instead, managers should enter discussions with a clear, balanced presentation of key issues and solutions, including specific recommendations for how any given audience can help. Specific suggestions are provided below.

Decision-makers. Senior managers, policy-makers and political leaders usually have responsibility for organisational priorities and allocation of funding and staff. Information about mass coral bleaching and its implications for the reef ecosystem, reef users and the wider community should be conveyed to decision-makers. This will ensure that coral bleaching is recognised as a management priority and incorporated into any relevant management decisions and strategies.

When briefing senior decision-makers, managers should strive to provide information early and to suggest actions that can be taken in response to the bleaching event, such as rapid impact assessments

In working with senior decision-makers, managers should strive to provide information early and to clearly articulate actions and solutions that can be implemented in response to mass bleaching events. A coral bleaching response plan is ideal for this purpose. The plan should outline a course of action and identify/estimate the resources required to implement it (see Section 2.1). In addition to immediate response actions, decision-makers should be informed of broader efforts that can be implemented to build coral reef resilience (see Chapter 3).

Formal briefings ensure decision-makers stay well informed and should be delivered in the lead-up to the bleaching-risk season and during major bleaching events. Written briefs should provide timely updates on the pending or current situation, and its environmental, economic, social and political implications. During a bleaching event, briefings are essential to ensure that senior management learn about significant developments prior to any public release of information. This is critical if institutional credibility and political support are to be maintained for the bleaching response as well as for any broader efforts to address mass coral bleaching. Overall, managers should aim to put senior decision-makers in a position where they can say, 'We know what's going on, and we are working hard to address the situation'.

Reef users. Reef users, such as recreational and commercial fishers, divers, and tourism operators, are likely to have a strong interest in the health of the reef and any major disturbances. They are among the groups most likely to be affected by any change in the quality of the reef, and may be key supporters of any efforts to mitigate localised stressors that reduce resilience or exacerbate the impacts of a bleaching event.

In working with reef users, managers should strive to foster a two-way exchange of information. Reef users can often assist the manager in understanding the status of bleaching at their site, and can provide anecdotal information on the sea temperatures, tidal conditions, and cloud cover that preceded the event. This information will allow the reef manager to better communicate the extent and severity of mass bleaching throughout the reef ecosystem, its effects, and its implications. Working together in this way can help raise awareness, build 'grass-roots' support for strategic management goals, and develop a shared understanding of the need for any short-term management actions. This is of particular importance because short-term actions may require restrictions on the types or levels of activities in order to minimise damage to the reef. The experiences of managers working with the diving industry in the Florida Keys National Marine Sanctuary (case study 4) and local fishers in Kenya (case study 5) are examples of using two-way communication during mass bleaching events to build support for broader management measures.

A community-based monitoring program not only provides valuable information about conditions on the reefs (see also Section 2.3.1), but also acts as an important and engaging communication tool. Involvement can convert a sense of helplessness into one of commitment to identifying and implementing practical actions. Reef users who are willing to contribute to community-based reporting programs are often the individuals and organisations who are leaders within the stakeholder community, and are ideal conduits for communication with the larger community. Their commitment to their industry or group,

CASE STUDY 4

Building collaborative partnerships with reef users during bleaching events – Florida Keys National Marine Sanctuary

Collaboration between reef users and managers can significantly improve the capacity of managers to respond rapidly to bleaching events. In the Florida Keys National Marine Sanctuary (FKNMS), the periodic occurrence of mass coral bleaching has provided an opportunity for coral reef managers to initiate valuable collaborative partnerships with dive operators.

During coral bleaching events in the 1990s, managers of the FKNMS involved dive operators in the early phases of their management response to coral bleaching. As soon as managers were aware that conditions were developing that could lead to coral bleaching, they communicated their concerns, and the scientific basis for them, to the dive operators. The managers used the HotSpot maps and degree heating keeks maps provided by NOAA to communicate the state of knowledge about the causes and predictability of coral bleaching.

Dive operators are often the first reef users to observe the early stages of coral bleaching. Dive operators and their customers are well placed to assist reef managers to monitor the extent and duration of bleaching, and of any secondary impacts that follow. As well as providing early observations of bleaching, divers and dive guides can assist managers in ground-truthing predictions of conditions known to cause bleaching, derived from remote sensing technology (such as satellite data).

The accuracy of the managers' predictions in the 1990 and 1997-98 mass coral bleaching events improved their scientific credibility with dive operators. The fact that coral reef managers could use remote sensing data from satellites combined with meteorological observations to predict coral bleaching events caught the attention of dive operators. This made it possible for managers to gain a mandate for responsive actions, such as research and monitoring, as well as education and outreach. Dive operators were also able to put in place measures to minimise visitor-related impacts on coral reefs stressed by bleaching. While dive operators routinely caution their customers against coming into contact with corals, the bleaching events provided another opportunity for operators to emphasise the vulnerability of corals to human activities.

In this case, bleaching events provided an opportunity for managers to form collaborative and mutually respectful relationships with a major segment of the tourism industry in the Florida Keys. These relationships have been maintained beyond bleaching events, and they continue to provide benefits in dealing with other management issues in the area.

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as well as to the reef, also makes them valuable partners in collaborative efforts to understand the problem and to devise appropriate solutions.

A community-reporting program can range in complexity from periodic face-to-face meetings and simple phone networks, to specially prepared surveys, with on-line reporting forms and summary reports. It is important that the primary mechanism for information exchange is appropriate to the target group. Active involvement will only occur if managers reach out and demonstrate a genuine interest in the knowledge and concerns of the stakeholders. Ongoing commitment from reef users to a reporting program will depend on their sense of the level of appreciation and utility of the information that they provide. For this reason, feedback is an important ingredient in the success of a community-reporting program. Managers should design active and transparent mechanisms for communicating to reef users how their information is being used. This may include regular dialogue by phone, email, or formal written summaries of conditions at the reporting site.

In addition to community monitoring programs, a number of strategies can be used to share information with reef users about mass bleaching. Managers should select the strategies most appropriate to their stakeholders, which may include speaking at community meetings, using local or industry newsletters, email updates, and the use of appropriate websites.

Good media coverage can significantly advance efforts to increase awareness about coral bleaching and create support for management initiatives

The mass media. A mass coral bleaching event is visually dramatic, attracts strong public interest and therefore, is highly likely to be considered newsworthy. Managers must be prepared to engage with the media in order to respond to questions and inquiries and, ideally, to utilise the media proactively as a communication tool. Good media coverage can significantly advance efforts to increase awareness about coral bleaching and create support for management initiatives. Professional training in media engagements can be extremely valuable in helping managers to maximise the value of media coverage.

Taking an active lead in interactions with the press will allow managers to influence the agenda of discussions and avoid being forced into a defensive position. There is value in meeting with the media before a mass bleaching event to educate, provide contacts, and offer resources. Media statements should be released as soon as new and significant information becomes available and senior decision-makers have been briefed. Managers should consider drafting generic media releases that can be annotated with the current facts and quickly released at key points throughout a bleaching event, such as when:

- conditions develop that indicate a high risk of coral bleaching
- a significant bleaching event occurs (describing spatial extent and general severity)
- the bleaching event has concluded (describing coral mortality and ecological impacts).

Managers should consider making available high-quality images for use by the press. Pictures of mass bleaching are available free of charge from many Internet sites including those listed in Section 2.6.3. High-quality still images of coral bleaching, especially those that have a strong human-interest element (for example a scuba diver or sea turtle in foreground) are often greatly appreciated by the print press. Similarly, television journalists will often be grateful for high quality underwater video footage. The provision of usable images helps foster a good working relationship with journalists, and increases the chance that media reports will highlight the manager's perspective on the issue. Where they exist, managers should work with in-house media experts to ensure that information is packaged appropriately for use by the different branches of the media, while maintaining key messages and factual correctness.

Although a well-prepared manager will usually be able to ensure accurate representation in press articles, there is always the risk that journalists will ask questions about issues that are politically sensitive to the management organisation. This is particularly true when the topic is coral bleaching, as journalists will frequently make links to politically sensitive issues. When a manager is speaking as a representative of an organisation, it is important that he or she has a clear understanding of the organisational protocols for interacting with the media. Working within organisational protocols is important to the manager's professional development and helps ensure access to future media engagements, one of the most powerful tools in the manager's response strategy. It is equally important to the achievement of effective public communication to maintain the trust of the journalist by not appearing evasive. Clearly defining boundaries prior to any media engagements will enable a manager to provide detailed and accurate information about the issue, while ensuring future opportunities to speak as a representative of the organisation. Strategies to deal with pointed questions on sensitive topics should be developed, and may include referring the journalist to a more relevant authority, such as climate scientists, the national meteorology or climatology agency, or a non-government organisation.

To achieve good results with the media, managers can consider meeting with reporters before bleaching starts, developing press releases with key facts, sharing quality images, and developing responses to questions about sensitive topics

Colleagues. Communication should be a collaborative endeavour, and will be most successful when done in close cooperation with colleagues, partner organisations, and other constituencies. Scientists and non-government organisations (NGOs) can be valuable partners in efforts to understand and communicate the effects of coral bleaching events, and to develop, communicate and implement potential mitigation strategies. Colleagues and fellow staff from within the manager's organisation are often overlooked in communication programs. Collegues are an extremely important audience for updates on bleaching conditions, as they will be major conduits to key sectors of the wider community for information about coral bleaching.

CASE STUDY 5

Involving fishermen in monitoring of coral reefs affected by bleaching in Kenya

The Kiunga Marine Reserve (KMR), in northern Kenya, is the site of a highly successful participatory monitoring program. The reserve designation allows traditional resource use including fishing, and artisanal fishers have been key participants in the program. The Kenya Wildlife Service (KWS) manages the reserve, while the WWF jointly operates a community-oriented project to raise awareness of the need for management in the area. The Coral Reef Degradation in the Indian Ocean (CORDIO) program gives technical assistance and partial funding for coral reef and fisheries monitoring.

Over its nine years of operation, a mix of fishers, WWF staff, KWS rangers, fisheries officers and researchers from the Kenya Marine and Fisheries Research Institute have participated in the monitoring program. It has been one of the largest annual activities in the KMR area that focuses exclusively on marine issues. This has given the monitoring program a social and communications prominence that has served to raise awareness of environmental issues in general, and particularly of the primary threats to coral reefs in relation to both climate change and fisheries.

The Kiunga Marine Reserve is one of the 'last frontiers' for fishing in Kenya, being protected by its remote location and harsh conditions. However, pressure has steadily increased from fishing communities to the south, repeating the common pattern from other parts of Kenya of invasion by migrant fishers from already depleted areas that use destructive fishing practices. Fishers resident within the reserve area have had a varying understanding of the extent to which these factors threaten their future livelihoods, with some welcoming and working with the newcomers as they bring immediate economic gain, while others have resisted change due to awareness of the longer term threat.

During the El Niño event of 1998, over 90 per cent of corals in the predominantly shallow reefs of the reserve bleached and died. The white corals were clearly observed by fishers, but their significance was not apparent due to the common belief that corals are 'stones' and therefore dead (the local name for coral is 'stone'). The participatory monitoring program offered a direct avenue for explaining the implications of the bleaching event to fishers. The threat posed to the local reefs by coral bleaching (a completely external threat) was used to emphasise the need to manage local threats, primarily recent increases in destructive fishing practices within the reserve.

Fishers were provided with information to help them understand the value of minimising local stressors so as to increase the capacity of reefs to regain their productivity in the face of threats beyond their control (such as climate change). In subsequent years, repeated sampling on the same reefs helped the monitoring team to appreciate the slow rate, and variability of recovery of coral communities.

In 2002 a program of coral transplantation was started, and seized upon eagerly by the fishers who were keen to attempt to rehabilitate reefs that showed little recovery. The fishers were warned that true rehabilitation would not happen with only transplanted corals, but the project provided an opportunity for them to get involved in a direct conservation intervention. The exercise has served to draw parallels between the practises involved in growing and caring for corals with those central to the indigenous farming culture: raising crops and animals, and watching over their slow growth and survival in a harsh environment.

The culmination of the first seven years of coral reef monitoring was a stakeholder workshop in May 2004 to develop the beginnings of a zoning and fisheries management plan for the Kiunga Marine Reserve. Fishers and marine reserve staff that have participated in the coral reef monitoring program have become key resource people in promoting the need for conservation management, and in facilitating the inclusion of their communities in planning stages. The leaders of the monitoring teams played a strong and active role in the workshop. Since the monitoring program was based on traditional fisheries zones and taxon names, presentation of reef health results was based on familiar geographic and ecological concepts to local communities.

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The monitoring team for the Kiunga Marine Reserve includes fishers, WWF staff, Kenya Wildlife Service rangers, fisheries officers and researchers from the Kenya Marine and Fisheries Research Institute, coordinated by David Obura from CORDIO (front right)

Communicating with colleagues can help managers better understand and respond to mass bleaching events – methods for sharing information range from formal websites and email list-servers to informal phone calls or seminar presentations

In working with colleagues, managers should strive to foster a mutual exchange of information and coordinate response and communication efforts. Effective communication channels should be established to share information and facilitate working partnerships. Collaborating on the development of response strategies can set the stage for partnerships of mutual benefit, as well as maximising consistency in methods that can facilitate comparison of results between sites and regions. An analysis of successes and failures can offer valuable learning opportunities, and shared experiences can rapidly accelerate collective improvements in knowledge and in the capacity to respond to bleaching events.

Methods for sharing information range from formal websites and email list-servers to informal phone calls or seminar presentations. Briefings about current conditions and the relevant management activities can be provided before and during bleaching events. Where the technology is readily accessible, email reports or websites are a rapid, cost-effective and far-reaching mechanism for disseminating information about 'current conditions' during bleaching events. Email reports can be sent to pre-existing email discussion groups or new lists can be generated and opened to self-subscription. Websites can be inexpensive to produce and need not require a high level of technical skill. The flexibility of a website enables the manager to present a range of information and photographs through separate, but linked, documents and to provide links to other sites of relevance (such as partner organisations).

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Communication between managers and stakeholders is a critical element of an effective response to coral bleaching

2.6.2 Frequently asked questions

While many of the questions that come up when talking to people about mass bleaching are predictable, they can be challenging to answer briefly and without technical jargon. This section provides examples of answers to eight common questions.

Q1: What is coral bleaching?

A1: Coral bleaching occurs when corals become stressed. Under stressful conditions, such as above-average water temperatures, pollutants or other stressors, the important relationship between corals and the microscopic algae that live within their tissue breaks down. These tiny algae, called zooxanthellae, provide corals with most of their energy requirements, as well as giving them their characteristic bright colours. When this relationship breaks down, the algae are expelled from the tissue, which then becomes transparent, allowing the white coral skeleton to be clearly visible. As a result, corals turn noticeably white, giving them the appearance of being 'bleached'.

Q2: Is coral bleaching bad for corals?

A2: Coral bleaching is a serious issue for corals. Mass bleaching events, caused by unusually high water temperatures, can lead to extensive coral mortality if temperatures are high enough (1-2 °C above long term summer maxima) for 4-8 weeks. During the worldwide bleaching event in 1997-98, coral bleaching caused catastrophic mortality at many reefs, including those around the Seychelles, Palau, Maldives and north-western Australia. However, bleached corals do not necessarily die. While many reefs have experienced mortality from coral bleaching, corals on many other reefs that have experienced mass bleaching events have suffered only minor levels of mortality. Providing warm temperatures do not persist for too long, zooxanthellae densities can return to normal. However, even corals that survive bleaching can suffer side effects, such as slower growth, lower rates of reproduction and increased risk of disease.

Q3: What causes mass bleaching?

A3: Many different stresses can cause corals to bleach, but mass coral bleaching occurs when water temperatures become unusually high. When temperatures become too high, the microscopic algae that live within the coral tissue are no longer able to cope with high light levels. As a result, they begin to produce molecules that are toxic to the coral, leading to their expulsion from the tissue.

When large areas of the ocean warm to unusually high temperatures, bleaching can affect corals over hundreds or even thousands of kilometres constituting what is known as a 'mass bleaching event'. High temperatures are projected to occur with greater frequency in many parts of the world over the century, leading to concerns that mass coral bleaching events will become an increasingly frequent and severe threat to coral reef ecosystems.

Q4: What will the impacts be to the affected reefs?

A4: Mass bleaching is a serious threat to coral reefs. While reefs are under pressure from many sources, few stresses have the potential to cause severe damage over such large areas. The unusually warm conditions that trigger mass coral bleaching can affect hundreds or thousands of kilometres. In these situations, extensive areas of coral reef can be severely stressed and potentially damaged. Importantly, the effects are not limited to corals. Damage from bleaching has the potential to affect all of the animals and plants that are part of the coral reef ecosystem, potentially impacting on reef biodiversity and the health of the entire ecosystem.

Q5 Why should people care about mass bleaching?

A5: Reefs that are damaged by coral bleaching are less appealing to tourists, they are less able to support fishing industries, and they may provide less shelter to coastal communities from storms and ocean waves. Recovery of degraded reefs can take decades, and the social and economic impacts can be long lasting. In Australia, for example, one study has estimated that coral bleaching on the Great Barrier Reef could cost the regional economy approximately US$100-300 million over 20 years[28]. In addition, reefs damaged by coral bleaching have lowered biodiversity and, quite simply, are less beautiful.

Q6: What does the future hold? Will mass bleaching events continue to be an issue?

A6: Reefs face a very uncertain future. Many are already under threat from land-based sources of pollution, recreational over-use and destructive or unsustainable fishing. The additional stress of mass bleaching events puts coral reefs at greater risk than ever before. Moreover, the threat of coral bleaching is expected to increase in coming decades. Climate scientists predict that the world's oceans will continue to warm, meaning that the frequency and severity of mass bleaching events is likely to increase. The abundance and vigour of corals is likely to decrease, with a potential shift to a predominance of algae rather than corals. This could have flow-on effects throughout the entire ecosystem, impacting on the full diversity of flora and fauna and the industries and societies that depend on healthy reefs. It is important to recognise that reefs are unlikely to disappear even under extreme climate change scenarios, but they will deteriorate in their ability to provide the ecosystem goods and services upon which human societies have come to depend.

Q7: Can anything be done about mass bleaching?

A7: Mass bleaching events pose a real challenge because there is little a reef manager can do to directly alter the climatic conditions that can cause coral bleaching. However, there are things we can do to help prevent and respond to bleaching. It is clear that reef managers can help build and sustain healthy reefs, and those healthy reefs may be better able to cope with the effects of coral bleaching than degraded reefs. Other stresses reduce a reef's ability to survive bleaching, and can delay or prevent recovery following severe bleaching events. Concentrating our efforts on managing the stresses that we can control, such as water pollution and overfishing, will help support the natural resilience of our reefs, and help maximise their chances of survival in the face of climate change and increasing human pressures.

Q8: What can our listeners/readers do to help?

A8: Listeners/readers can help by becoming more involved in the management and conservation of coral reefs. These precious ecosystems are under unprecedented pressure and need every bit of help they can get. People who visit the reef regularly can help by reporting coral bleaching if they see it. We have a website/information kit/contact person to help members of the public learn about coral bleaching, how to recognise it on the reef, and how to report it.

2.6.3 Resources

There are a number of resources available to help managers to integrate bleaching-specific elements into management and to communicate with stakeholders about mass bleaching. There are many excellent resources available on the broader subject of coral reef management. The list below, includes resources that specifically relate to mass coral bleaching events.

- The Nature Conservancy (TNC) and partners have produced a multimedia CD-ROM toolkit entitled: *Reef Resilience: building resilience into coral reef conservation*. This Reef Resilience (R^2) toolkit (www.reefresilience.org) provides resource managers with cutting-edge strategies and tools to lessen the impacts of coral bleaching and conserve reef fish spawning aggregations. The toolkit is designed to help practitioners begin to build resilience into coral reef conservation programs so that their reefs might better survive mass bleaching events in the future.

- ReefBase (www.reefbase.org) is a global information system for coral reef conservation and management developed by WorldFish Centre, Penang, Malaysia. It provides managers with monitoring data and advice on coral reefs, and stores all records from the Global Coral Reef Monitoring Network (GCRMN) and Reef Check. Worldwide coral bleaching reports, maps, photographs, and literature are available on the website, and bleaching reports can be submitted online for inclusion into the databases.

- The Great Barrier Reef Marine Park Authority (Australia) (www.gbrmpa.gov.au) has developed a volunteer program called 'BleachWatch' to encourage dive operators and other regular users of the reef to monitor for bleaching in areas they frequently visit. Similar programs have also been developed for use in Bali Barat National Park (Indonesia) and the Florida Keys National Marine Sanctuary (USA). BleachWatch kit materials, such as an armband showing degrees of bleaching and reporting forms printed on waterproof paper are designed specifically for these types of reef users so that they can easily note and report any bleaching with minimal inconvenience to their normal operations. The GBRMPA website is also a source of information and images relevant to coral bleaching.

- The Coral Reef Alliance (www.coralreefalliance.org) hosts the International Coral Reef Information Network library online. Bleaching papers, briefing sheets, reports and other information can be accessed online.

- The National Oceanic and Atmospheric Administration (NOAA) Coral Reef Conservation Program (www.coralreef.noaa.gov) provides a number of tools and resources related to coral bleaching events such as Coral Reef Watch (CRW). Coral Reef Watch provides three tools that analyse satellite imagery to assess the likelihood of mass coral bleaching events. These products are freely available over the Internet, and include: HotSpot maps, degree heating week maps, and Tropical Ocean Coral Bleaching Indices. Other tools and information are available through NOAA's Coral Reef Information System (www.coris.noaa.gov).

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CHAPTER 3

BUILDING LONG-TERM REEF RESILIENCE

3. BUILDING LONG-TERM REEF RESILIENCE

There is widespread agreement that increasing coastal populations and projected increases in sea temperatures will continue to increase pressures to coral reefs, and that the need for effective coral reef management has never been greater[9, 11, 13, 23, 28, 31, 42, 47]. Management efforts that increase reef resilience will play a critical role in determining the future of coral reefs by allowing species to adapt and adjust before irreversible damage occurs[75]. The concept of resilience is based on well-established scientific principles, and its use in strategic management of coral reefs offers insights and approaches that are becoming increasingly critical for the protection of these complex ecosystems.

In the context of mass bleaching, resilience can be thought of as the integrated result of coral resistance to heat stress, coral survival during bleaching, and reef recovery after bleaching-related mortality (Section 3.1). Managers can take active steps toward restoring and maintaining the long-term resilience of coral reef ecosystems. Managers can support coral reef ecosystem resilience in two ways: (1) by incorporating existing resilient areas into management design; and (2) by implementing strategies to either reinstate or protect factors that confer resilience, such as good environmental conditions, biological diversity, and connectivity.

Incorporating resilient areas into spatial networks for reef management requires knowledge of the location of resilient reefs. There is an emerging knowledge of how to identify and classify these areas (Section 3.2).

Factors that confer resilience can be reinstated or protected using a range of conventional management strategies that focus on management of local stressors. MPAs can be used to manage direct threats to reefs, such as those that may result from fishing and recreation practices (Section 3.3). Broader management approaches, such as watershed management and integrated coastal management (ICM) can manage indirect threats to reefs, such as those resulting from coastal developments and agricultural land use (Section 3.4). In some cases, restoration measures may also be appropriate to increase overall resilience (Section 3.5). While there may already be management action directed at localised issues such as fishing, pollution and recreation, controls may need to become more conservative given predicted increases in the frequency of bleaching events[9]. This section explores ideas about coral reef resilience and the management actions that can build resilience in the context of mass coral bleaching.

Two ways of supporting coral reef ecosystem resilience are (1) by incorporating existing resilient areas into management design and (2) by implementing strategies to either reinstate or protect factors that confer resilience, such as good environmental conditions, biological diversity, and connectivity

3.1 Resilience

Coral reef ecosystems are highly dynamic systems that have evolved to cope with a wide range of disturbances. While a resilient system will have the best chance of coping with future threats, human influences have eroded the natural resilience of many coral reef systems, reducing their capacity to cope with disturbance. Strategies aimed at rebuilding and supporting the resilience of these systems are the best investment for ensuring that reefs can continue to provide the goods and services upon which humans depend[11, 76]. This section introduces the concept of resilience and describes the factors that confer resilience on coral reef ecosystems.

3.1.1 Defining resilience

Ecosystem resilience relates to the ability of the system to maintain key functions and processes in the face of stresses or pressures by either resisting or adapting to change[76, 77]. For coral reef ecosystems, resilience characterises the capacity to maintain the dominance of hard corals and/or to maintain morphological diversity, rather than shifting to a predominantly algal state or a single coral morphology. Resilience also includes the potential of the system to reorganise and build its capacity to adapt to change[78]. As an example, a resilient coral community might suffer significant coral mortality from a bleaching event, but reorganise so that the community composition shifts toward different coral species that provide similar habitat and are more tolerant to coral bleaching.

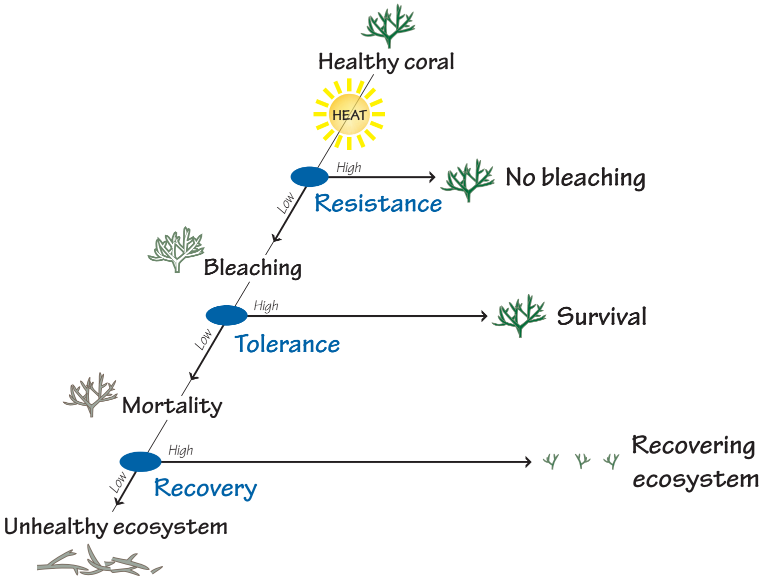


Figure 3.1 Coral reef ecosystem resilience to mass coral bleaching

Ecosystem resilience relates to the ability of the system to maintain key functions and processes in the face of stresses by either resisting or adapting to change. The resilience of coral reef ecosystems to mass coral bleaching can be thought of as the integrated result of coral 'resistance' to heat stress, coral 'tolerance' during bleaching events, and reef 'recovery' after bleaching-related coral mortality. 'Resistance' determines the extent to which corals either withstand exposure to heat stress or bleach. Once bleached, tolerance determines the extent to which corals either survive the bleaching event or die. When coral mortality is high, reef recovery determines the extent to which the system either re-establishes coral dominance or remains degraded. Coral resistance, coral tolerance, and reef recovery are determined by a number of factors that can be broadly grouped into four categories: (1) ecosystem condition, (2) biological diversity, (3) connectivity between areas and (4) local environmental conditions. Implementing actions that either protect or strengthen these four resilience-conferring factors can help coral reef ecosystems survive predicted increases in the frequency and severity of mass coral bleaching events. Adapted from Obura (2005)[88].

In the context of mass bleaching, resilience can be considered as the capacity of the coral community to resist, survive, or recover after recurrent bleaching events (Figure 3.1). A resilient reef may suffer significant coral mortality during a bleaching event, but will maintain key system characteristics (structure and function) through rapid recovery and reorganisation, relative to less resilient reefs. The capacity of coral reefs to recover from disturbances will become increasingly important if the frequency and severity of bleaching events increases. Reefs with lowered resilience are more likely to suffer serious and long-lasting impacts from coral bleaching events.

In a broader context, the cumulative effects of global and local stressors will determine the long-term resilience of coral reef ecosystems. While both global and local stressors can support or degrade the factors that confer resilience on reef ecosystems, local stressors are much easier to manage in the short term. These resilience factors are discussed below. Implications for the management of local stressors are discussed in Sections 3.3 and 3.4.

3.1.2 Factors that confer resilience

Factors that influence the resilience of coral reef ecosystems can be grouped into four categories: (1) ecosystem condition, (2) biological diversity, (3) connectivity and (4) local environment. Each of these categories includes attributes that can strengthen resistance, survival, and recovery from mass bleaching as well as recovery from other types of disturbances.

Ecosystem condition. Ecosystem condition includes coral condition, coral cover, water quality, and fish abundance. These attributes influence survivorship during mass bleaching events and recovery after mass bleaching events or other disturbances. Corals that are stressed or in poor condition, as indicated by low lipid levels, suppressed immunity, or high levels of stress metabolites, may be less likely to survive the stresses associated with coral bleaching[41]. Coral cover, water quality, and fish abundance are critical factors determining reef recovery through their influence on a range of processes including: larval supply, availability of substrate for settlement, coral recruitment rates and survivorship of juvenile corals (see Section 4.2.3). Management efforts that effectively strengthen ecosystem condition are likely to play a major role in facilitating recovery processes in reefs affected by climate change[47].

Coral condition, amount of coral cover, water quality, and fish abundance are attributes of ecosystem condition that are likely to play a major role in determining coral reef ecosystem resilience to climate change

Biological diversity. Biological diversity plays an important role in determining resilience, especially through the influence of genetic diversity within species and species diversity within ecosystem functions. These attributes influence coral resistance to bleaching, coral survivorship during bleaching, and reef recovery after mass bleaching mortalities or mortalities from other disturbances. In particular, genetic variation in zooxanthellae may play a role in influencing resistance to mass bleaching[79]. Genetic differences between corals also strongly influence the outcome of bleaching events, with coral type being a major determinant of a coral's susceptibility to bleaching and the rate at which it can recover from bleaching[80].

The importance of these sources of diversity becomes increasingly significant over time as reef ecosystems are repeatedly exposed to thermal stresses. When a diversity of species fulfils a function (for example branching corals providing habitat for small fish), the loss of a single species will not lead to loss of the function. This functional redundancy is a key characteristic of resilient systems[81]. Biological diversity also plays a practical function in protecting ecosystems from future threats through maximising the diversity of responses[11]. A system is less prone to collapse when key functions are performed by multiple species that respond differently to stress or disturbance events. Like functional redundancy, response diversity minimises the chance that any one disturbance will eliminate all organisms performing a key function.

The importance of biological diversity in conferring resilience is well illustrated by the role of herbivores in coral reef ecosystems. In a case study from Jamaica[82], overfishing had prevented herbivorous fishes from playing a significant role in controlling algal growth. At that point, the herbivory function, which works to ensure the availability of substrate suitable for new coral recruits, was dependent on the sea urchin, *Diadema antillarum*. Subsequently, a disease epidemic killed most of the urchin population, leaving too few herbivores in the system to adequately remove algae. When a major storm caused widespread damage to coral communities, unchecked algal growth prevented substantial recovery of corals. These reefs have remained algal-dominated for decades. Overfishing and reduced functional redundancy made the system highly susceptible to disturbances and led to a phase shift towards an algal-dominated system with a substantially lower capacity to provide ecosystem services to humans. If a diversity of herbivores had been present and fishing pressures better managed, the system would have been protected through functional redundancy and less prone to collapse.

Biological diversity confers resilience because different species are likely to respond differently to stress and disturbance events, increasing the chance that some species will survive and continue to perform key ecosystem functions

Connectivity. The capacity of a system to recover or reorganise following a disturbance is an important element in determining resilience. Connectivity plays a central role in determining this potential as it influences the likelihood that damaged reefs will be replenished by 'seed' reefs or refugia. In the context of resilience, it is important to realise that connectivity is more than larvae drifting in largely unmanageable ocean currents. Much of the connectivity in reef ecosystems depends on intact and healthy non-reef habitats, such as inter-reef hard bottom communities or seagrass beds[83]. These non-reef habitats are particularly important to the maintenance and regeneration of populations. They will become increasingly critical as reef systems spend greater time in recovery mode due to severe and more frequent disturbance events, such as temperature-related coral bleaching. Management efforts that provide effective protection for each of the critical habitat types will play a key role in restoring and maintaining the capacity of the coral reef system to adapt to increased frequency and severity of mass coral bleaching.

Connectivity plays a central role in determining coral reef ecosystem resilience as it influences the likelihood that damaged reefs will be replenished by 'seed' reefs or refugia.

Variation in the local environment can determine coral reef exposure to heat stress, light levels, or current speed – all factors that influence coral reef resilience to bleaching

Local environment. Variation in the local environment can determine exposure to heat stress, light levels, or current speed – factors that influence resistance and tolerance to bleaching. For example, exposure to heat stress will vary depending on location within the reef (such as reef flat compared to reef slope) or, at a larger scale, a reef's orientation with respect to upwelling. In some situations, shading from cliffs or mountains along the shoreline can reduce light levels and decrease bleaching risk. In this context, topographic complexity can play an important role in determining the amount of variation in the local environment of corals. This further increases the imperative for reef managers to protect species diversity and thereby minimise the chances of reducing variation in the local environment. The role of local environmental factors in resilience makes it a useful feature for identifying resilient areas, as discussed in the next section.

3.2 Identifying resilient coral reef areas

Identifying coral reef areas that are resilient to mass coral bleaching and protecting these areas from localised stressors offers the potential to create a network of refugia that can replenish other areas that are more vulnerable to bleaching

The severity of bleaching responses varies between reefs during mass bleaching events[19 118]. Identification of areas that have historically had high resilience to bleaching provides the basis for a network of refugia to underpin resilience-based management of the reef ecosystem. Refugia serve as a seed bank to facilitate the recovery of areas with lower natural resilience, and will play a central role in networks of protected areas designed to maximise ecosystem resilience.

The identification of resilient areas as an ecosystem management strategy is already being applied in various locations around the world. Examples of resilience-based management initiatives include projects in Palau (A. Smith, pers. comm.), the British Virgin Islands (S. Wear, pers. comm.), Belize (S. Walsh and M. McField, pers. comm.), the Seychelles (J. Neville, pers. comm.), Yemen[84], and the Maldives (G. Dews, pers. comm.). The experiences gained from these initiatives will help to refine knowledge and develop additional protocols for the identification of resilient areas. The outcomes of these early tests of resilience management strategies will also provide important information about the extent to which the factors that confer resilience on an area will remain consistent over time.

The Nature Conservancy, together with a group of partners, has developed a *Reef Resilience (R^2) Toolkit* to help managers develop and apply resilience principles for managing coral reefs[39]. This section draws from the R^2 toolkit to review the features that characterise resilient reefs (Section 3.2.1), and to outline how to identify areas of high resilience (Section 3.2.2). Managers are directed to the R^2 toolkit or website (www.reefresilience.org) for a more detailed discussion of how to identify resilient areas and incorporate these areas into MPA design.

3.2.1 Characteristics of resilient coral reef areas

Patterns of past bleaching responses, mortality and reef recovery provide insights into an area's resilience to mass coral bleaching events. Based on evidence from the literature and systematically compiled observations from researchers in the field, a number of factors that correlate with resilience to coral bleaching have been identified[40]. Resilience to bleaching is associated with features that:

- Reduce sea temperature stress, eg localised upwelling, proximity to deep or cooler water
- Increase water movement in order to flush harmful toxins, eg topographic features such as narrow channels, strong currents
- Screen corals from damaging radiation, eg high island shading, reef shelf shading, aspect relative to the sun, or water turbidity
- Indicate potential pre-adaptation to temperature and other stressors, eg highly variable temperature regimes, regular exposure at low tides, history of corals surviving bleaching events
- Indicate strong recovery potential, eg abundance of coral larvae or strong recruitment
- Improve coral larval transport to the site, eg connectivity with source reefs
- Maintain a favourable substrate for coral larval recruitment, eg diverse community structure present, healthy and stable populations of herbivores.

3.2.2 How to identify resilient areas

There are two broad approaches to selecting reef areas that are likely to be resilient to mass coral bleaching: (1) identifying areas based on their response to past incidents of anomalous sea surface temperatures and (2) predicting areas based on the presence of characteristics expected to confer resilience.

Identifying resilient areas from past responses. The response of corals and reef communities during previous bleaching events can provide important pointers to sites that may be inherently resilient to coral bleaching. There is uncertainty about the extent to which past patterns will be repeated during future mass bleaching events, and data should be interpreted carefully. In addition, identifying sites that display a demonstrated resilience to bleaching requires reliable information about levels of heat stress during bleaching events, and knowledge about the extent of bleaching for sites of interest. Figure 3.2 (based on Done et al[85]) provides a decision tree for identifying areas to target for management based on their resilience to past sea temperature anomalies.

A site's potential resilience is one of several factors that should guide decisions relating to the selection of areas for increased management. The first step in a management planning process is to identify candidate sites based on conventional criteria for site selection. The eligibility of sites for protection should be evaluated on the basis of social, economic, ecological, regional or pragmatic criteria[86]. The criteria used should be carefully chosen so that the selection process meets the specific objectives of the planned management regime.

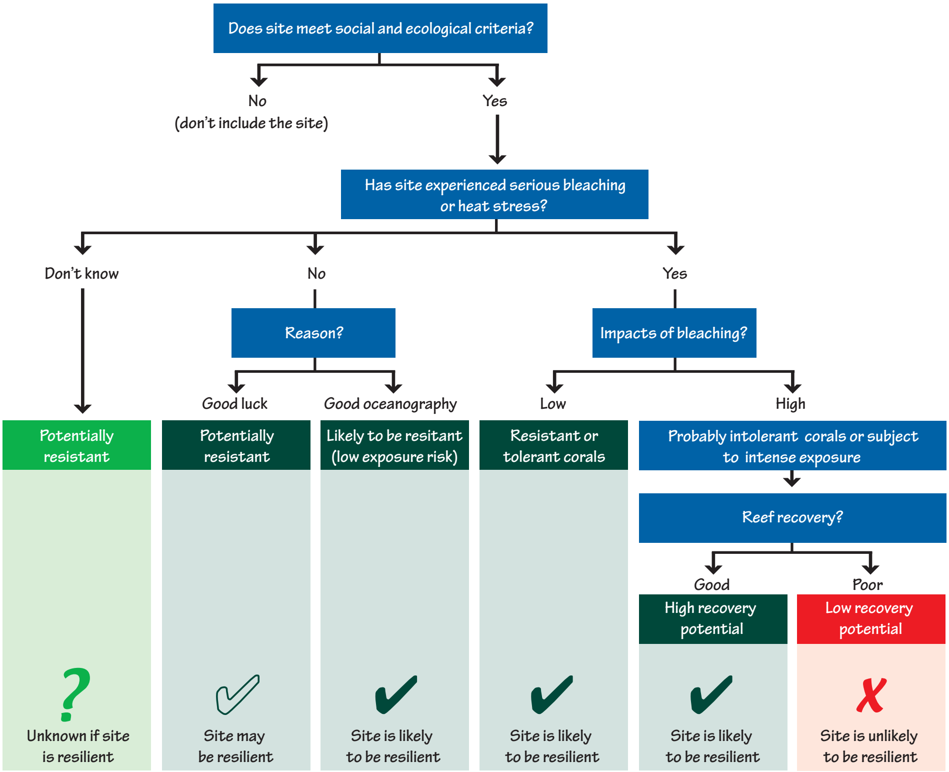


Figure 3.2 Decision tree for identifying resilient areas for increased management based on past responses to heat stress and bleaching (adapted from Done et al[85])

Coral reef community response during previous bleaching events can provide important pointers to sites that may be inherently resilient to coral bleaching. If a site warrants increased management protection based on conventional social and ecological selection criteria (see Salm et al[86] for further discussion about selection criteria), its potential resilience can be assessed by first evaluating its historical exposure to heat stress. A site that has not experienced previous exposure to stressful temperatures may be resilient to mass bleaching, depending on the reasons for its good luck. A site that has been exposed to stressful temperatures may still be resilient to mass bleaching if it has been tolerant to the bleaching event and exhibited high levels of coral survival. Finally, sites that suffered high coral mortality during past bleaching events may still be resilient if the site has demonstrated a good rate of recovery (years rather than decades).

At each of the candidate sites, heat exposure and past bleaching responses should be evaluated. Sites should initially be divided into those that have experienced serious bleaching or heat stress previously, and those that have not. Current information about thermal stress, presented as sea surface temperature anomalies, is now readily accessible to most reef managers through the NOAA HotSpot program, freely available on the Internet (see Section 2.2.2). HotSpot maps (50 x 50 km) visualise differences in exposure to thermal stress at a larger spatial scale. This can be readily supplemented with reef-scale measurements obtained from direct temperature readings with thermometers or inexpensive data loggers. Local bleaching thresholds can then be refined by maintaining temperature records and correlating measures of thermal stress with observed bleaching responses.

It is revealing to examine possible reasons for some reefs having no recorded history of anomalously high water temperatures. If sites have low risk of exposure to high water temperatures because of their oceanography or other physical characteristics, they may prove to be resistant to bleaching in the future. In examining the reasons for low exposure, it may be useful to question whether the feature conferring resilience in the past is likely to remain unchanged in the future. For example, shading from cliffs is unlikely to change but currents may shift under various climate scenarios. However, in many cases it may not be possible to identify the mechanisms or characteristics that have resulted in a site being spared exposure to heat stress. In other cases, it may not be possible to ascertain whether a site previously experienced heat stress. In both of these situations, the resilience of the reef community to bleaching has to be assessed using other criteria, such as community composition and recovery rates following recent disturbances. Managers should consider implementing a monitoring program at these sites to document their response to any future episodes of thermal stress.

The next step is to examine the response of reefs that are known to have experienced thermal stress in the past. Reefs that have suffered only minor coral mortality during previous anomalies are likely to be populated by corals that are resistant to bleaching, or that have a high tolerance for bleaching. These reefs are probably sites of high resilience, unless they were only exposed to minor stress. If the latter is the true case, then it is difficult to predict whether they are likely to be resistant or tolerant to more extreme temperature stresses in the future.

Determining the thermal history of reef sites can be difficult, especially if managers do not have access to historical satellite-derived or in situ temperature data. However, even in remote locations there may be long-term temperature monitoring programs being run by researchers or other organisations (such as meteorological or shipping agencies). Local knowledge should also be sought and collated, as some regular reef users, such as tourism operators and fishers, have an intimate, longer-term perspective about the conditions on their reefs that can help deduce the occurrence of anomalies.

The remaining category of sites includes those that have suffered substantial mortality following exposure to stressful temperatures. The rate of recovery at these sites provides important information about their resilience. Damaged sites that show high rates of recovery are resilient. Sites with low rates of recovery are not resilient, unless the causes of slow recovery can be identified and remedied by management action.

Predicting areas of resilience. In many instances, it may not be possible to assess the response of reef sites to thermal stress. This may be because bleaching has not occurred in the past, or because there is not sufficient information about either the exposure of different sites to high sea temperatures or its effect on reef organisms. In these cases, reef managers may still be able to include bleaching resilience in their management plans by identifying areas that are characterised by factors that are known to contribute to resilience.

Section 3.2.1 outlines a set of key characteristics that have been identified from observations of the characteristics of reefs that have proven resilient to past bleaching events, or have been derived from general principles of coral community dynamics. The R^2 Toolkit provides detailed guidance and data sources for gathering information about these characteristics. Table 3.1, adapted from R^2, summarises information sources that can be used to assess these characteristics and, thus, predict site resilience to mass bleaching. The role of these characteristics in conferring resilience to mass coral bleaching events is explored below.

The R^2 Toolkit identifies five characteristics thought to confer resilience to mass coral bleaching: cool water, shading, screening, resistant coral communities, and high recovery rates

1. Cool water. Some sites may have consistently cooler water due to upwelling or proximity to deep water. Local bathymetry, regional and local currents and prevailing winds may all play an important role in reducing the temperature of water bathing a reef. Case study 6 describes research that is developing hydrodynamic models of Palau to predict future sea temperatures in order to identify areas that may be protected from mass bleaching by cooler waters. Some researchers have suggested that currents may not be a reliable source of long-term resilience because climate change may result in new current patterns[87].

2. Shading. Some reefs may also be protected from bleaching stress by shading where sun exposure is limited by topographic or bathymetric features. Reefs shaded by cliffs or mountainous shorelines may be at reduced risk of bleaching. While many reef areas are unlikely to be associated with features that can provide shade, fringing reef complexes around steep-sided limestone or volcanic islands, such as occurs in Palau and the Philippines, may have many shaded sites.

3. Screening. Unnatural levels of sediments and excessive phytoplankton growth from nutrient-enrichment can stress and kill corals. However, naturally turbid conditions may filter or screen sunlight, providing a measure of protection for corals exposed to anomalously warm water. Ongoing research suggests that organic matter in turbid areas may absorb UV wavelengths and screen sunlight. Corals at these sites may be less susceptible to bleaching. However, turbid conditions are often sub-optimal for coral reef development, and biological diversity may be low in these areas.

4. Resistant and tolerant coral communities. Knowledge about the composition of coral communities can also help predict sites that are more resilient to bleaching. Observations during past bleaching events from around the world indicate that

certain types of corals are generally more resistant to bleaching than others[80]. If a site is dominated by resistant species, then any temperature-induced bleaching is likely to be less severe (Box 4.1 in Section 4.2 shows key coral groups in order of bleaching resilience). Similarly, certain corals appear to be able to survive in a bleached state for an extended period and are, therefore, less likely to die even if they bleach. While less work has been done on bleaching tolerance, it appears that corals with a massive morphology and thick tissue, such as those from the families Poritidae, Favidae and Mussidae, have greater tolerance to bleaching[118].

Another observation is that different colonies of the same species can vary in their bleaching response, and one mechanism that has been identified for this variation is differences in the types of zooxanthallae hosted within the coral tissue[79]. Case study 7 describes work being done on the Mesoamerican reef to assess the importance of stress-tolerant zooxanthallae in determining the severity of bleaching as part of a broader initiative to identify potentially resilient areas.

5. High recovery rates. The ability to recover, and the rate of recovery, after a mass bleaching event is another relevant characteristic of coral reef resilience. Sites that recovered well from previous disturbances, such as storms, are more likely to recover quickly from bleaching events. Where recovery rates are not known, managers can infer a site's capacity for recovery by evaluating whether conditions are conducive to coral recruitment and survival.

Table 3.1 Characteristics and information sources for predicting the relative bleaching resilience of candidate reef sites

Availability of information sources will depend on level of resources or expertise, and are divided into low, moderate and high resource requirements.
1.Cooler due to upwelling or proximity to deep water
• Consult nautical almanacs, charts, local fishers, online NOAA resources[1], and University of Hawaii[2] website to identify and assess exposure to regional and local currents. Look at the location of islands and reefs to infer how prevailing currents might cause mixing and water-cooling.
• Local studies that release dye, use drogues, or release drift cards or floating instruments can give some information on surface current movements.
• Conduct shipboard studies of underwater and surface currents. Use oceanographic models of water movements.
2. Protected by shading
• Check topographic maps of islands and mainland coasts indicating likely areas of shading. In particular, look for high, steep islands and coasts with cliffs. Mapping of the ocean floor and the topography of the reef can be used to describe the aspect (angle to the sun) of particular reef faces.
• Direct observation of shading-by snorkellers and divers, from boats, or by time-lapse photography or video-can be used to quantify sun exposure. Correlation with the presence or absence of bleaching in shaded locations during or after a bleaching event can also indicate the impact of shading.
• Use a network of light meters to measure and correlate sunlight exposure over time with bleaching and mortality patterns.
3. Protected by screening by suspended particles and dissolved matter
• Use satellite imagery, aerial photos, or direct surveys to identify areas with consistently lower water clarity.
• Measure suspended sediments and turbidity along transects with a Secchi disc, turbidometer, or other instruments.
• Take scientific measurements of sunlight penetration and quantitative measurements of CDOMs.
4a. Coral community dominated by bleaching-'resistant' corals
• Compile existing data or local knowledge about composition of coral communities at candidate sites. Identify dominant coral groups and give them a bleaching resistance ranking based on Box 4.1.
• Conduct surveys of coral community composition at candidate sites and assess relative dominance of coral types known to be more resistant to bleaching.
• Conduct physiological studies of dominant corals at candidate sites to measure likely resistance indicators, such as zooxanthellae type and photoprotective pigments.
4b. Coral community dominated by bleaching-'tolerant' corals
• Compile existing data or local knowledge about composition of coral communities at candidate sites. Give dominant coral groups an indicative bleaching tolerance ranking based on morphology (massive > encrusting > branching/tabular) and tissue thickness or 'fleshiness'. Corals with good capacity for heterotrophic feeding should be assessed as having higher bleaching tolerance, where this information is known.
• Conduct surveys of coral community composition at candidate sites and assess relative dominance of coral types known to be more tolerant of bleaching (using criteria above).
• Conduct physiological studies of dominant corals at candidate sites to measure likely tolerance indicators, such as tissue condition (lipid levels) and heterotrophic capacity.
5. Demonstrated strong recovery
• Use existing data or local knowledge to identify areas with a good mix of old and young corals. Previous studies or anecdotal observations may help identify reefs that have rapidly recovered from other disturbances such as storm damage or COTS (*Acanthaster*) outbreaks.
• Undertake field surveys to identify those places where coral cover and species diversity quickly recovered following an earlier known bleaching event. Use point, line or quadrat survey methods to measure changes in coral cover and community composition following bleaching- induced mortality at candidate sites. The presence of high numbers and diversity of early coral recruits, and the prevalence of conditions known to be conducive to survival and growth of young corals, can also indicate strong recovery potential.
• Develop models to predict recovery capacity from ecological dynamics that include recovery-supporting processes, such as larval supply, connectivity and physico-chemical conditions that enhance coral survival and growth.

[1] www.noaa.gov/

[2] www.soest.hawaii.edu

A major research program to improve predictions of coral bleaching in Palau

A collaborative program involving experts from The Nature Conservancy, the US National Oceanic and Atmospheric Administration (NOAA) and the Australian Institute of Marine Science is taking a detailed look at the role of sea surface temperature (SST) in major bleaching events. The goal of the project is to improve predictions of coral bleaching in Palau, but the knowledge gained from the study will be valuable to other regions.

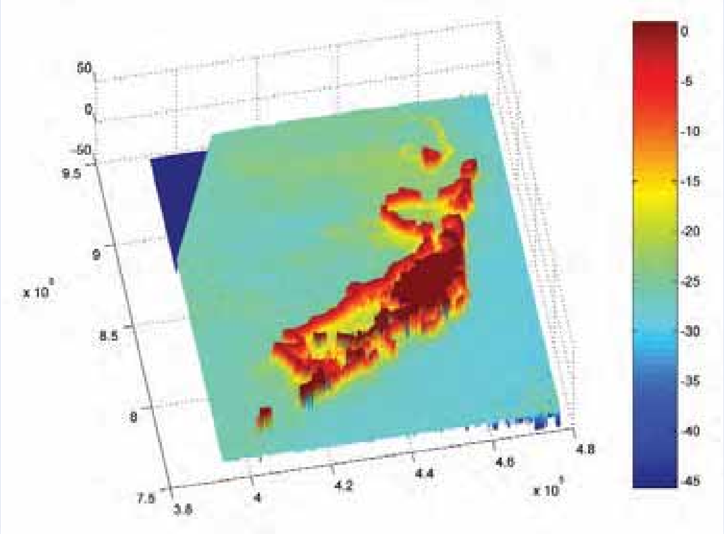
Modelling patterns of thermal stress

One of the major environmental stresses that cause bleaching of corals is heightened water temperature. Over 98 per cent of solar radiation energy is absorbed within the top four metres of the water column. This heat will stay at the top of the water column unless there is a mechanism to mix it with the cooler water below. Vertical mixing occurs in regions of relatively strong horizontal currents; these can be associated with surface winds, large-scale currents (for example the Gulf Stream) and tides. Therefore, extended periods of cloudless summer days with low winds and low currents create conditions known to induce bleaching events.

Hydrodynamic models can be used to predict SST patterns for a future, severe, mass coral bleaching event. Thus, they provide an excellent tool for managers, particularly when designing Marine Protected Area networks. Hydrodynamic modelling can also assist in the investigation of other issues that relate to the coral reef ecosystem. Connectivity with biological events (for example coral/fish spawning) and human activity (such as sewage outfall and pollution accidents) can be monitored and/or predicted.

Calibration and validation of the hydrodynamic models for the Palau project will be carried out by comparison of the model results with in situ data. Seventy instruments were deployed across the Palau lagoon to record data for a five-month period, from August 2003 to January 2004. The instruments included current meters, conductivity sensors, temperature profiles and pressure gauges. Atmospheric conditions were recorded during the same period using a dedicated weather station. In addition, vertical profiles of conductivity and temperature with depth were measured three times at several locations during the study.

One of the most important inputs to a high-resolution hydrodynamic model is the bathymetry. Since there was no reliable source of high-resolution bathymetry for Palau, this project endeavoured to generate one. This was achieved by merging a global bathymetry data set with satellite-derived depth data, and validating these with a series of transects collected from small boats.



Bathymetry map developed for Palau by merging global bathymetry data with satellite-derived depth information

Studies of bleaching events on the Great Barrier Reef, Australia, have demonstrated how the hydrodynamics during a coral bleaching event can be predicted with reasonable accuracy. The methods used in this study will be used to increase our understanding of the climatic and physical conditions conducive to rapid seawater warming to help understand the process of heat dissipation within lagoonal and barrier reef systems. It is expected that the study will highlight the importance of micro-environments, local topography, and reef hydrodynamics in determining the severity of bleaching during periods of anomalously high sea temperatures. In addition, during the Palau study, additional research is being undertaken to further develop the technology and capacity to predict coral bleaching events.

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CASE STUDY 7

Understanding patterns of bleaching in the mesoamerican reef – a collaborative effort to support resilience-based management

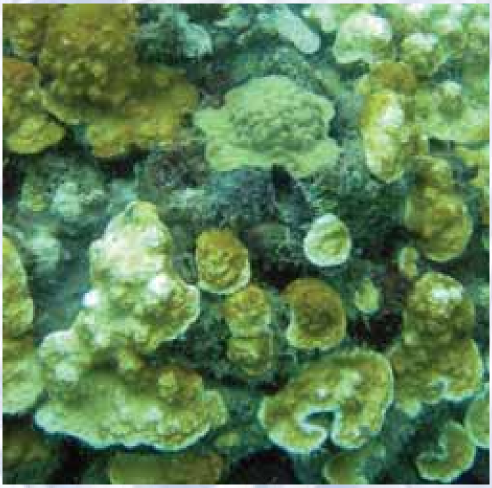
Bleaching on the Mesoamerican Reef

The Mesoamerican reef includes the longest barrier reef in the western hemisphere, with a diverse array of associated reef types. The core of this reef system, in Belize, did not suffer a major bleaching event until 1995, when approximately 10 per cent of colonies suffered at least partial mortality[155]. More recently, there have been dramatic declines in live coral cover attributed to the 1997-98 bleaching, including severe mortality on nearly 100 per cent of central lagoonal reefs and 50 per cent of 12 fore-reef sites studied. These losses have been associated with the combined effects of bleaching and a hurricane[156, 157]. Several regional threat assessments have identified the increased frequency of coral bleaching events associated with climate change as a primary threat to the region[158, 159].

A collaborative program

In response to concerns about the future of this reef ecosystem, the WWF, The Nature Conservancy (TNC), the Wildlife Conservation Society (WCS) and Scripps Institution of Oceanography are collaborating in an attempt to understand the variability in responses observed during past bleaching events. These agencies hope to determine whether this may provide a basis for resilience-based management of the region. This work will use TNC's Reef Resilience (R^2) Toolkit to help design and field-test a conceptual model of reef resilience. The model will be based on natural variations in key environmental conditions and incorporate the latest research on reef connectivity.

Understanding the characteristics that actually confer resilience on any given reef will provide managers with specific targets for conservation. It will also provide one of the key criteria in ongoing efforts to develop and implement a full representational analysis of the region's Marine Protected Areas network. A variety of approaches will ultimately be needed to address this issue, but one novel avenue currently being studied by Scripps and the WWF involves the characterisation of the abundance and distribution of zooxanthellae in various reef habitats. Furthermore, knowledge about zooxanthellae distributions will assist managers to decide whether this approach could play a role in the design of management strategies.



© Melanie McField

Coral bleaching can be highly variable, even within a single coral colony

CASE STUDY 7

Variability in coral bleaching

Different coral species can vary substantially in their response to thermal stress, independent of zooxanthellae type[80]. Yet, different colonies of the one species can also vary in their bleaching response, and one mechanism that has been identified for this variation is differences in the clades of zooxanthellae hosted within the coral tissue. Different clades of zooxanthellae respond differently to stress, leading to patterns of coral bleaching that often cannot be explained by coral taxonomy alone[160]. Experimental bleaching of corals and studies of the distribution of zooxanthellae suggest two potential explanations for the observed patterns of bleaching[161, 162]. The first is that corals may resist bleaching by associating with stress tolerant zooxanthellae. The second suggests that corals may be able to survive future bleaching events by repopulating with stress-tolerant zooxanthellae[162, 163].

Monitoring to understand resistance to bleaching

Beginning in 2003, researchers from the Scripps Institution of Oceanography and from the WWF, Belize, began surveying the presence of stress-tolerant zooxanthellae within reefs and in adjacent reef habitats. One theory that emerged from this survey is that the amount of bleaching that occurs at each reef may be influenced to some extent by the prevalence of stress-tolerant genotypes of zooxanthellae. Identifying the patterns and sources of zooxanthellae diversity will provide information on the role of zooxanthellae composition in determining the effects of thermal stress on coral communities, which may assist managers to evaluate the potential resilience of different sites.

Using research to help managers support reef resilience

Following bleaching events, researchers and managers will work together to assess the importance of stress-tolerant zooxanthellae in determining the severity of bleaching during future thermal stress events. Combining the monitoring of zooxanthellae diversity with other key factors for reef resilience will allow managers to better understand what makes a specific reef resilient. In turn, this will help them adapt management strategies so that the focus is on protecting those factors most important for maintaining reef resilience.

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3.3 Using Marine Protected Areas to increase resilience

Marine Protected Areas (MPAs) can help build coral reef resilience by supporting and enhancing the factors that confer resilience: good coral reef condition, biological diversity, connectivity, and favourable local conditions. Traditionally, principles of MPA selection, design and management have not specifically addressed the threat of mass coral bleaching[89]. This section considers the additional considerations that are relevant to MPA site selection (Section 3.3.1) and management (Section 3.3.2) in the context of mass coral bleaching.

Expected increases in the extent and severity of mass coral bleaching warrants the inclusion of additional, resilience-related criteria in MPA site selection

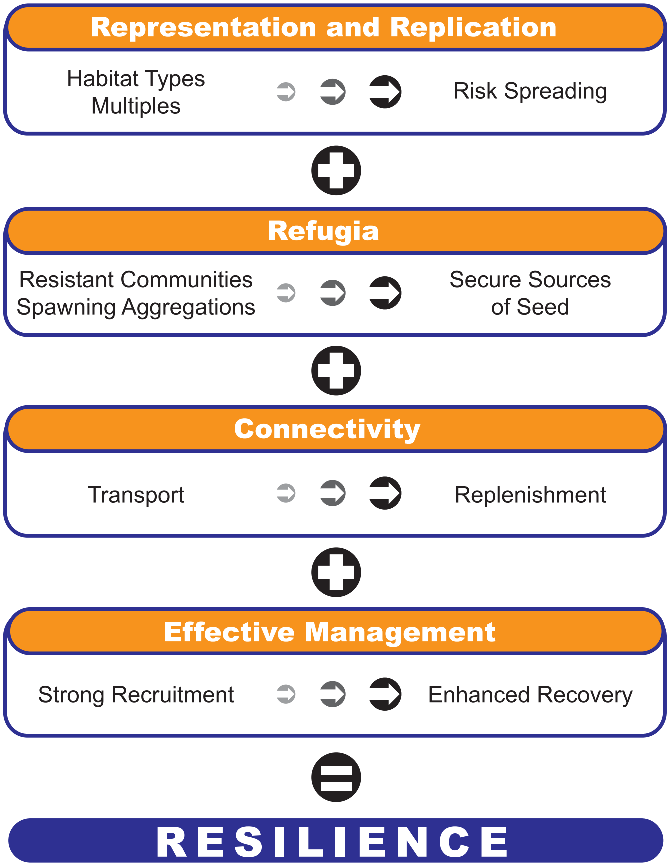

Figure 3.3 Principles for building resilience into MPA design

The Reef Resilience (R^2) Toolkit, developed by TNC, identifies four key principles to help incorporate coral reef resilience into MPA design (www.reefresilience.org).

3.3.1 Selecting MPA sites in the context of mass coral bleaching

Expected increases in the extent and severity of mass coral bleaching warrants the inclusion of additional, resilience-related criteria in MPA site selection (Figure 3.3). Importantly, the resilience principles outlined here are meant to build on existing MPA selection criteria and design principles, not to replace them. Existing MPA planning approaches, including appropriate stakeholder engagement strategies, remain essential for defining conservation objectives, identifying threats and determining management strategies to address these threats. The intention of these additional resilience principles is to enhance the role of selected sites in contributing to improved resilience of the ecosystem.

1. Representation and replication. Sometimes called 'spreading the risk', this principle recommends that, in the uncertain context of climate change, MPA network design should aim to replicate a range of reef types and related habitats. Section 3.1.2 describes how protecting biological diversity confers resilience to coral reefs. This principle aims to maximise biodiversity as a way of increasing the chance that among these species and habitats there will be enough survival and recovery to maintain functional coral reef ecosystems.

2. Refugia. The refugia principle aims to take advantage of coral reef areas of natural resilience, as identified in Section 3.2. In the context of mass coral bleaching, refugia can serve as 'seed banks' or source reefs for less resilient areas. For refugia to serve this role, they must be effectively protected from local stressors, such as anchor-damage, over-fishing or pollution, and thus are high priority for increased management attention.

3. Connectivity. Connectivity plays an important role in coral reef resilience by promoting recovery after mass coral bleaching events and other disturbances (see Section 3.1.2). Implementing this principle in MPA design involves considering prevailing currents and adjacent non-reef areas. Linking MPAs along prevailing, larvae-carrying currents can replenish downstream reefs, increasing the probability of recovery at multiple coral reef sites. Adjacent non-reef areas are important to connectivity because they can become important staging areas for coral recruits as they move between reefs and into new areas.

4. Effective management. Coral reef ecosystems in good condition are better able to survive and recover from mass bleaching events (see Section 3.1.2). This principle refers to effectively managing local stressors at a site in order to optimise coral reef condition. High coral cover, abundant fish populations and good water quality are all elements of coral reef ecosystem health that support recovery. To implement this principle, MPA selection should give priority to sites where levels of resource use and effective management can help maintain these supportive attributes.

3.3.2 Managing MPAs in the context of mass coral bleaching

Once sites are selected for inclusion in an MPA network, managers must decide on the management objectives and management regime for each protected area. Again, in the context of mass bleaching, management can increase reef resilience by strengthening or taking advantage of factors that confer resilience: good coral reef condition, biological diversity, connectivity and favourable local conditions[90, 91]. Marine Protected Areas are particularly suited to managing direct threats to coral reefs, such as those from over-fishing and recreational overuse or misuse. While MPAs can assist in addressing indirect threats, such as land-based pollution, achieving this goal usually requires broader management activities (see Section 3.4).

A high-level objective of MPA management in the context of resilience should be to protect fish abundance, with an emphasis on herbivorous fishes. The role of herbivores in maintaining conditions that are conducive to coral recruitment and survival[3] makes their protection critical for reefs subject to increasing sea temperatures (see Section 2.5.2). While some level of harvest may be sustainable, the importance of herbivores to future reef resilience means that managers should carefully manage fishing activity to ensure adequate levels of herbivory are sustained (a conservation objective), and not merely to ensure a sustainable or maximum harvest (a fisheries objective)[11].

Managing the impacts of recreational use of MPAs is another way managers can support the resilience of reef ecosystems. Recreational activities can result in physical damage from diving and boat anchoring, and from release of nutrients and combustion products from vessels (see Section 2.5.2). Where MPAs have been established to protect important bleaching refugia, even localised stresses associated with recreational activities may pose a significant threat to resilience. MPA managers should carefully control snorkelling, diving and boat usage to minimise stress to corals, especially during or following a bleaching event. In most cases, these are sites within MPAs and/or sites with high visitation rates. While MPA managers may already have regulations and best-practice guidelines in place, measures to ensure users avoid imposing additional stresses during periods of temperature stress should be considered.

3.4 Broader management interventions to increase resilience

Many managers have a range of authorities and tools that can be used to protect resilient reef areas from local stressors and to increase coral reef resilience. These include fishery regulations, tourism permitting, coastal development regulations and watershed management. Expected increases in the frequency, spatial extent and severity of mass coral bleaching events will have implications for effective application of these traditional management tools. At present, these implications are largely understood as conceptual principles that will benefit from refinement with additional experience and research. The approach taken by The Republic of the Seychelles following the 1997-98 mass bleaching event, described in case study 8, is a good example of how these principles can be put into practice.

CASE STUDY 8

Identifying resilient areas for improved protection of Coral Reefs of the Seychelles

Responding to the devastating impacts of coral bleaching in the Seychelles

The Republic of the Seychelles, located in the western Indian Ocean between 4° and 11° south of the Equator, was one of the areas most severely affected by the global mass bleaching episode of 1997-98. In this area, sea temperatures exceeded 30°C for several months. Coral mortality due to bleaching was extremely high, with declines of 85-95 per cent in the cover of structurally dominant branching corals (*Acropora* and *Pocillopora*) on the reefs surrounding the inner granitic islands of the group. These islands, Mahé, Praslin and La Digue, are home to 95 per cent of the population of the Seychelles.

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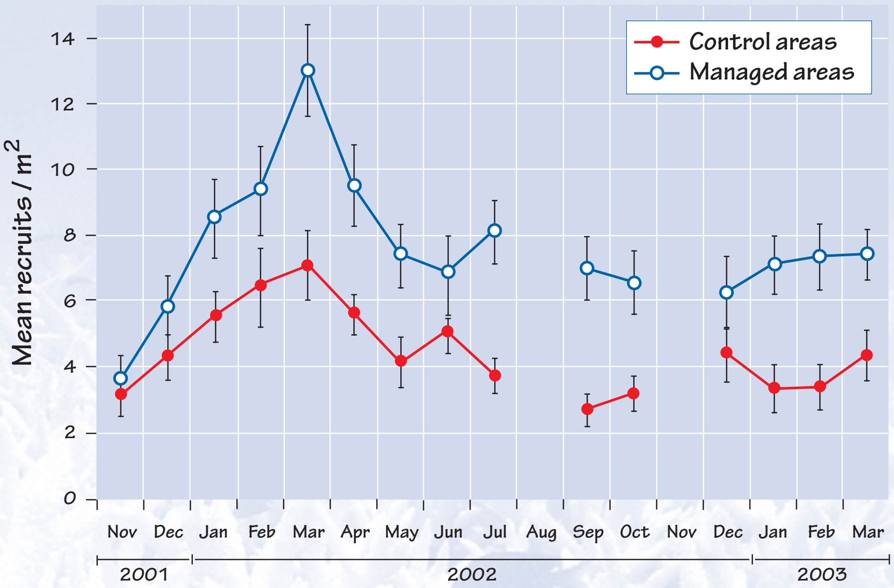
Sailing and other reef-oriented tourism activities are an important use of coral reefs in the Seychelles

In the Seychelles, coral reefs are particularly important to social and economic sustainability. Following the 1998 event, the Government immediately initiated a collaborative program to facilitate and promote the recovery of damaged reefs, and to identify focal sites for future conservation efforts. The program focused on rebuilding the resilience of reefs in the region. The Seychelles Marine Ecosystem Management Project (SEYMEMP) was established to facilitate the recovery of coral reefs, guide the management of existing marine protected areas (MPAs) and develop strategies to improve the protection of reefs against future coral bleaching events, or other negative impacts. Major aims for SEYMEMP included:

- assessment of the impacts of the 1997-98 coral bleaching event on corals and associated fish communities
- identification of areas resistant to bleaching, and of areas that have demonstrated strong recovery
- investigation of factors that could interfere with coral reef recovery and the development of tools and strategies to promote recovery of degraded reefs.

Some sites are showing signs of resilience

Detailed ecological monitoring of benthic transects since the 1997-98 coral bleaching event have identified reef sites that are demonstrating good recovery. These sites are showing strong trends in the increase of hard coral cover, increasing from an average of less than five per cent to 15-20 per cent in six years. This compares to an average of 10 per cent cover after six years for all sites combined. Hard coral diversity has also shown strong signs of recovery at these sites, with many now having a significant proportion of the species typical for the region. Significantly, however, the reefs of the Seychelles were affected by bleaching events again in 2003 and 2004, impeding or reversing recovery at many sites. There was an interesting contrast in the effect of these more recent events on *Acropora* and *Pocillopora* corals, with the latter showing a strong decline in recovery rates while the recovery trajectory for *Acropora* (pooled across species) was generally unaffected.



Average density of coral recruits in managed areas (urchins removed) and control areas (urchins not removed)

This graph shows the mean number of acroporid and pocilloporid coral recruits per 1 m^2 (0-5 cm size class) in areas subject to high grazing pressure by black-spined sea urchins (control areas, red line), and areas where sea urchin densities were maintained at a lower level through active population management (managed areas, blue line).

Coral recovery is threatened by overgrazing

At many sites, the distribution and density of grazing sea urchins (*Diadema* spp. and *Echinometra* spp.) appears to have increased in recent years. This is believed to be due to the reduction in the number of fishes known to prey on these mobile invertebrates. Grazing of hard substrate by urchins affects recruitment of hard corals because settling larvae are consumed along with the targeted algae. At locations where grazing is intense, recovery is limited, or inhibited entirely. Experimental efforts to control sea urchin density proved to be effective in increasing coral recruitment, with a doubling in the abundance of *Acropora* and *Pocillopora* recruits over a 12-month period in areas where urchins were removed, as compared to control areas. Consequently, reef managers are considering control of sea urchin populations to facilitate recovery within MPAs. Priority areas for this management response are close to coral communities with a demonstrated resilience to bleaching, either by surviving the bleaching event with minimal mortality, or by rapidly recovering.

Some sites were protected by proximity to upwelling

Three reef sites with the fastest rates of recovery–Marianne Island Reef, Aride Island Reef and Anse Petit Cour Reef at Praslin–suffered minimal coral mortality. This resistance occurred despite the sites being characterised by a relatively diverse community of hard coral species, many of which did not survive elsewhere. It is probable that these sites benefited from cold-water upwelling, and they are likely to be important seed sources for replenishment of depleted coral communities. These refugia are being considered for special management measures designed to improve the resilience of the entire system following impacts from future bleaching events.

Management actions to protect coral refugia

Some of the sites shown to have higher resilience to repeated bleaching events are outside the boundaries of existing MPAs, indicating that there is value in considering increased protection of these sites through future incorporation into the MPA network in the Seychelles.

One site identified as a refuge from bleaching-induced mortality is already protected within an MPA, but was being threatened by anchor damage associated with heavy tourism use. Moorings have been installed to minimise anchoring in the area, and ongoing monitoring has shown that, as a result, the damage to coral has been significantly reduced.

This case study demonstrates the importance of regular monitoring and adaptive management in responding to emerging threats, such as coral bleaching. The strong partnerships among government agencies, non-government organisations and stakeholders and local communities have resulted in a better understanding of the effects of past coral bleaching events, and identified strategies to support reef resilience. This initiative provides the foundation for efforts that will help the reefs of the Seychelles to continue recovering from the mass bleaching event of 1997-98 and maximise the chances that they will survive future bleaching events.

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3.4.1 Guiding principles

The following three principles were identified by participants of an international workshop on 'Coral Reefs, Climate Change, and Coral Bleaching' that was hosted by the US government in 2003. At the workshop, a group of experts was brought together to suggest how mass coral bleaching could be integrated into broader coral reef management efforts given the existing limitations in our scientific understanding. Their recommendation was to manage adaptively for the factors that confer resilience and the cumulative effects of multiple stressors.

Manage for the factors that confer resilience. Broader reef management efforts have a key role to play in supporting the factors that confer reef resilience (see Section3.1.2). In particular, efforts to address indirect threats to reefs that degrade coral reef condition can normally not be achieved through MPAs alone and require integrated, collaborative coastal management. Examples of indirect threats include degraded water quality that might result from coastal development or agricultural land use.

Recognise the cumulative effects of multiple stressors. Under the additional threat of mass coral bleaching, management of localised stressors may need to become more conservative in order to help maintain ecological condition and services. Managers need to consider how targets for and expectations of fish abundance, water quality, and physical damage from recreational use might be revised to reflect the cumulative impacts of global and local stressors. Ecological modelling can assist managers in this process by identifying the relative importance of different management goals (Box 3.1).

Manage adaptively. A key issue for implementation of broader measures to build reef resilience is the limited information available. Current understanding of the factors that confer resilience is based largely on scientific principles, rather than empirical studies. The importance of maintaining high coral cover, abundant herbivore populations and good water quality in promoting resilience is widely acknowledged (see Section 4.2.3). Yet, the complexity of the ecosystem and the state of scientific knowledge mean that managers must continue to make pragmatic decisions and implement management actions in an environment of considerable uncertainty.

The adaptive management approach provides a valuable framework for active management in the face of uncertainty[40, 78]. It may be particularly appropriate in the context of coral bleaching where there is a strong imperative to respond to a highly visual event despite the absence of complete knowledge. Adaptive management recognises that management actions can be taken in a hypothesis-driven framework where management is an iterative learning exercise rather than a 'solution' to a well understood problem. Reflecting on what has been learned at each stage of the management process provides insights about how future management actions can be refined or 'adapted'. Adaptive management can also be helpful in fostering innovation and collaboration in management, attributes that are likely to accelerate progress in identifying productive approaches to future management in the context of mass coral bleaching.

Taking an adaptive management approach to managing reefs in the context of climate change can help foster innovation and collaboration in management that accelerates progress in identifying productive future strategies

Box 3.1 Using models in coral reef management

The processes driving coral reefs occur on a wide range of spatial and temporal scales. Given the complexity of such systems, there is an increasing need to use models to answer some of the questions posed by managers. For example, an empirical study is unlikely to deliver a prompt answer to the question, 'What level of fishing pressure can be tolerated given scenarios of increasing sea temperature and cyclone activity?'. However, in constructing answers, models can be a powerful asset when used in combination with good empirical data.

Models have two main uses in science. First, they help us understand the relative importance of single factors in the dynamics of complex systems (sensitivity analysis). The modeller may create a simplified version of the reef and then test the plausibility of alternative scientific explanations, or the relative effectiveness of different management scenarios. For example, managers may use a model to investigate how changing one condition (for example the abundance of herbivores) can influence the rate of recovery on a reef impacted by coral bleaching. Moreover, a variety of factors can be modified in tandem to investigate whether certain combinations affect the reef's recovery more than others do. These models can identify critical aspects of the ecosystem that disproportionately influence reef resilience. Managers can then consider how to reduce stress at these critical parts of the system.

The second use of models is that of prediction. For example, given our present ecological understanding of scenarios for future climates, what percentage coral cover will be found on local reefs in 2050? Although models based on ecological data can be used for prediction, there are many scale issues to consider. For example, it is difficult to reconcile the impact of a warming climate with the daily foraging of parrotfishes within a single model. Therefore, different types of models are appropriate for different questions, and an optimal solution would use a range of inter-connected models at different scales. In general, predictive models need a firm basis in probability so that the confidence in the predictions is made abundantly clear.

Modelling the conditions on reefs in relation to coral bleaching and management strategies is a very active, but relatively new, area of research. Whilst a number of groups are working on various models, few results have yet been published. The paper by Woodridge et al (2005)[47] illustrates the potential of modelling to support resilience-based management in the context of coral bleaching. Further information can be found from individual research groups including AIMS Reef Futures (www.aims.gov.au/reeffutures), the Marine Spatial Ecology Lab (www.ex.ac.uk/msel) and the National Centre for Caribbean Coral Reef Research (NCORE, www.ncoremiami.org).

3.5 Reef restoration strategies

Recent worldwide reports of reef damage due to mass bleaching events, combined with projections of future warming trends, indicate that reef managers should expect reefs to continue to deteriorate[5, 9]. Although the natural resilience of reef ecosystems will facilitate recolonisation and subsequent recovery of sites that suffer significant coral mortality, full recovery to pre-disturbance coral cover and diversity can be an extended process, requiring many years, and usually many decades[133,134]. The recovery process can be further lengthened, and even inhibited, if the natural resilience of the reef ecosystem has been eroded through other pressures, such as excess nutrients or sediments, habitat damage or over-harvesting of key functional groups[88, 93].

In some instances, following severe bleaching-related coral mortality, reef managers may wish to consider proposals to assist or accelerate natural recovery processes through active restoration. Many techniques come under the banner of reef restoration. Some of these techniques are only appropriate in very specific circumstances. Care must be taken to use only those techniques appropriate to the reef in question and to the nature of the disturbance that has affected it.

In some instances, following severe bleaching-related coral mortality, managers may wish to consider assisting natural recovery through active restoration

The logistics, costs and effectiveness of restoration activities as well as any legal considerations should be carefully examined before deciding on a course of action[94]. Cost-effective approaches and technologies are still in the early stages of development, and, in most cases, are currently not viable for implementation on large spatial scales. Given the extreme cost of some of the techniques, especially coral transplantation, careful consideration is needed when deciding whether to use available funds for restoration of a small area or for initiatives with broader influence, such as education and preventative measures.

The diversity and scale of experimental restoration approaches used to date vary widely[94]. They cover habitat modification, coral transplantation, species re-introduction and enhancement of recruitment. Some of these interventions involve large-scale, sub-tidal structures designed to facilitate natural colonisation of reef-related species[95-97], while others use simpler and less costly approaches that are more readily replicated[98-100]. The following sections examine restoration issues in detail.

3.5.1 Considerations for reef restoration strategies

Several overarching considerations are central in deciding whether to pursue restoration strategies. These include: Is restoration the best use of limited resources? Will restoration efforts endure in the long-term, given the expected recurrence of bleaching? Will restoration efforts be effective under the current and expected regime of other stresses? Is there legal or socioeconomic justification for the undertaking of restoration? This section examines these issues in more detail with the aim of assisting managers to make decisions on the use of restoration measures in response to coral bleaching events.

Before implementing restoration, managers should evaluate whether selected strategies will be cost-effective, endure in the long-term and are able to achieve desired results

Is restoration the best use of resources? Restoration of coral reefs is an extremely expensive exercise[101]. For example, the costs for extensive restoration efforts following ship groundings have ranged from US$10 000 to an estimated US$6.5 million per hectare[102]. If there is no need to repair structural damage, and only coral transplantations are carried out, the costs can be much lower. However, even in these situations, it is likely to cost tens of thousand of dollars per hectare just to achieve a realistic target of 10 per cent coral replacement cover[103]. Furthermore, these costs are based on trials in which only a few fast-growing genera, with high aesthetic values and fast growth rates (such as *Acropora* and *Pocillopora*) were used[103-105].

In light of the immense costs that are involved in coral transplantation, the ethics and appropriateness of spending resources for such small-scale projects must also be considered. The largest coral transplantation projects carried out to date involved an area of 7.1 hectares, which highlights the limited scale over which transplantation techniques can be applied. A relatively cost-effective approach using rock piles has been recently demonstrated in Komodo (Indonesia) over a six hectare area, suggesting potential for rehabilitation of larger areas[106]. Yet, these spatial scales are still extremely small compared with the scale of damage that can result from mass bleaching events. Nevertheless, restoration strategies may continue to be appropriate for small sites of high value, such as significant tourist destinations. Even in these circumstances, however, managers will want to be sure that restoration efforts will result in lasting improvements.

Will restoration efforts endure? Even if funding and technical constraints were to be overcome, investment in coral reef restoration efforts will be wasted if chronic stresses that could be exacerbating coral mortality or hindering recovery are not managed. Mass coral bleaching is expected to be a recurrent phenomenon over coming decades, making it probable that restored sites will, in the near future, suffer a similar disturbance to that which motivated the restoration effort. Two approaches can be adopted, both based on current understandings of restoration and specifically addressing degradation caused by bleaching. For reefs that have survived past bleaching events, restoration can target the enhancement of resilience by promoting biodiversity. For reefs with a poor recovery record from bleaching, restoration should aim at promoting growth of tolerant species and providing shading against increased solar radiation.

Will restoration efforts be effective? Numerous experiments and case studies of reef restoration indicate the difficulty in achieving restoration success. Technical and financial constraints force a bias toward fast-growing coral genera in restoration projects, making it very unlikely that direct restoration will restore the impacted resource to a level that is functionally equivalent to pre-disturbance conditions. Furthermore, the survivability of transplanted corals is variable and subject to many factors beyond human control, leading to uncertain ecological outcomes.

3.5.2 Restoration methods

Direct, site-based restoration efforts that might be contemplated in response to bleaching-induced mortality can be divided into three main categories: coral transplantation, 'seeding' with coral larvae and reinstatement of herbivores. The potential benefits and limitations of each of these are discussed below.

Coral transplantation. An examination of case studies demonstrates that most aspects of coral reef restoration, coral transplantation in particular, are still at an experimental stage. The limited-scale projects implemented to date demonstrate clearly that coral transplantation is a very costly exercise, with uncertain ecological outcomes[103,104]. In fact, coral transplantation introduces the risk of adverse outcomes, such as shifts in community structure, the transfer or introduction of diseases, or interference with the natural gene flow, and impacts on the donor colony or reef[105]. Harm to existing corals and reefs can be minimised by using in situ coral mariculture to supply transplantation operations with corals adapted to natural reef conditions. The viability of in situ nurseries[107] has been demonstrated with propagation of loosely-scattered colonies in a sheltered, lagoon-like reef area[108]. Yet, even at small spatial scales, the costs and benefits of coral transplantation require careful consideration before it is used for reef management purposes. Over spatial scales normally affected by mass coral bleaching events, coral transplantation is extremely unlikely to be financially viable.

In summary, coral transplantation should be viewed as a strategy of last resort, and should only be undertaken at small, high value sites where there is strong justification for accelerating natural recovery processes. If natural recovery is hindered by other stresses, such as poor water quality or excessive algal growth, management efforts should be prioritised to address these issues before investment is made in coral transplantation.

Coral 'seeding'. An alternative method to transplanting adult colonies to accelerate recovery is 'coral seeding'. This technique involves collecting larval slicks from broadcast spawners for direct transfer to an impoverished site, or 'staging' the slicks in protected habitats to allow larvae to settle before transferring to the target site[109]. Coral larvae may also be reared under laboratory conditions until they are competent to settle, and then released into eddies associated with target reefs. Larval retention times of 1-3 weeks inside eddies are believed to promote enhanced local settlement. Although untested, proponents of this technique have suggested that coral seeding will result in regeneration rates of possibly two orders of magnitude higher than can be achieved by transplantation efforts[109].

Several concerns are relevant to coral seeding as a restoration technique. The method has not been widely tested, so its effectiveness in different circumstances is not well known. The practicalities of the method, especially in relation to costs, logistical requirements and expertise have not been explored for a range of settings. The ability of seeding to assist recovery to full (pre-disturbance) species diversity is not known, but is likely to be significantly limited. Furthermore, in most situations, damaged reefs will be supplied with natural sources of coral larvae from upstream source reefs, particularly when management schemes promote habitat connectivity. Coral seeding is only likely to be warranted in situations where a reef is very remote or has only limited connections with upstream sources of larvae.

In summary, coral seeding techniques are still largely in the developmental stage, and present many of the concerns and limitations associated with coral transplantation. However, with further development and in some limited circumstances, they may prove to be a more cost-effective method for increasing recovery at defined sites[109].

Reinstate herbivores. In some situations, natural recovery of reefs following bleaching-induced mortality may be hindered by excessive growth of filamentous or fleshy algae[45]. On many reefs, over-harvesting of herbivores, especially fishes, can lead to excessive algal growth[42]. This, in turn, results in reduced availability of the bare substrate required for settlement of coral larvae.

While the effects of reduced herbivory may not be obvious in an intact coral community, the effects of low recruitment rates resulting from excessive algal growth may be severe following a major disturbance such as bleaching-induced mortality[44]. Although the over-harvesting of herbivores from a coral reef system should be of concern to reef managers for a diversity of reasons, the effects of a coral bleaching event can dramatically increase the urgency of efforts to address this problem[11].

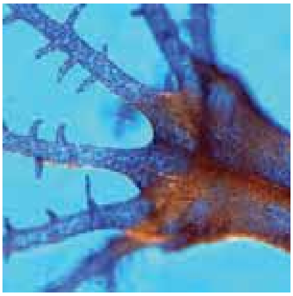
Widespread mortality of corals should trigger renewed efforts to prevent further, unsustainable, removal of herbivores from the system. This could entail greater limits on fishing activities or increased penalties for non-compliance with fishing restrictions. However, in situations where herbivore populations are already depressed due to heavy harvesting, passive management (such as the removal of fishing pressure) may not be enough to ensure herbivore populations recover. This is particularly relevant in locations where reef recovery is limited by excessive algal growth caused by chronically depressed herbivory levels. In these cases, managers may need to consider active reinstatement of herbivore populations. This might require captive rearing of herbivores, or perhaps methods of enhancing reproduction and recruitment of key herbivore species. Importantly, techniques of actively restoring herbivore populations remain to be tested, and the feasibility of this method requires further investigation.

CHAPTER 4

CORAL BLEACHING – A REVIEW OF THE CAUSES AND CONSEQUENCES

4. CORAL BLEACHING – A REVIEW OF THE CAUSES AND CONSEQUENCES

The mass coral bleaching events that have occurred throughout the tropics over the last decade have provided unprecedented opportunity, and motivation, to study this phenomenon. As a result, knowledge about the causes and consequences of coral bleaching has increased substantially in recent years. This accumulating body of information is providing critical advances in our understanding and has generated new insights, which can assist reef managers to respond to the threat of coral bleaching. This section aims to provide a summary of recent developments in the science of coral bleaching, highlighting emerging knowledge and recent insights that are most relevant to reef managers.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The zooxanthellae can be clearly seen as golden-coloured dots in this close-up image of a coral polyp. The symbiotic relationship with these tiny dinoflagellates enables corals to gain energy from sunlight

4.1 What is coral bleaching?

4.1.1 The coral-algal symbiosis

The great majority of corals live in a symbiotic relationship with zooxanthellae, a type of single-celled dinoflagellate algae. These microscopic algae live within the coral's tissues. Zooxanthellae produce energy-rich compounds through photosynthesis, providing a food source that is absorbed and used by the coral. In general, corals are highly dependent on this symbiotic relationship, receiving up to 90 per cent of their energy requirements in this way[17].

Bleaching is a stress response that results when the coral-algae relationship breaks down. The term 'bleaching' describes the loss of colour that results when zooxanthellae are expelled from the coral hosts or when pigments within the algae are degraded. Because the photosynthetic pigments found in zooxanthellae give corals most of their colouration, the loss of zooxanthellae renders the tissue largely transparent. The white of the calcium carbonate skeleton is then clearly visible through the un-pigmented tissue, making the coral appear bright white or 'bleached'[24]. Bleaching also occurs in other animals that are engaged in symbiotic relationships with zooxanthellae, such as foraminifera, sponges, anemones and giant clams.

Bleaching is a stress response that results when the coral-algae relationship breaks down

In some instances, coral bleaching will result in corals taking on a pastel shade of blue, yellow or pink rather than turning bright white. This is due to proteins produced by some corals, which tint the coral tissue and become the dominant pigment during bleaching, when zooxanthellae are absent[110, 111].

It isn't only corals that bleach; other organisms that have zooxanthallae, such as this (a) giant clam and (b) anemone can also bleach in response to thermal stress

4.1.2 The causes of coral bleaching

Mass coral bleaching affects reefs at regional to global scales – it is primarily caused by unusually high sea temperatures

The primary cause of mass coral bleaching is increased sea temperatures[9,13,18,23,53]. At a local scale, many stressors including disease, sedimentation, cyanide fishing, pollutants and changes in salinity may cause corals to bleach. Mass bleaching, however, affects reefs at regional to global scales and cannot be explained solely by localised stressors operating at small scales. Rather, a continuously expanding body of scientific evidence indicates that such mass bleaching events are closely associated with large-scale, anomalously high sea surface temperatures[8, 9, 13]. Temperature increases of only 1-2°C can trigger mass bleaching events because corals already live close to their maximum thermal limits[9, 23].

The role of temperature and light. Increased temperatures cause bleaching by reducing the ability of the photosynthetic system in the zooxanthellae to process light. When temperatures exceed certain thresholds, incoming light overwhelms the photosynthetic apparatus, resulting in the production of reactive oxygen species that damage cellular structures[24, 112]. Corals cannot tolerate high levels of these toxic molecules, and they must expel the zooxanthellae to avoid tissue damage. Because of the low tolerance of the photosynthetic process to high temperatures, even normal levels of sunlight are enough to damage the photosynthetic system of the zooxanthellae when temperatures exceed certain levels[23, 113]. Furthermore, as light levels increase the amount of damage due to thermal stress increases as well[24].

Bleaching is reduced in shaded reef areas because light levels influence the amount of damage caused by temperature stress

The relationship between temperature and light in causing coral bleaching helps explain observations of reduced bleaching on shaded parts of coral colonies or in shaded reef areas[9, 114, 115]. It also suggests that the spatial extent and patterns of bleaching responses may be influenced by factors that determine the amount of solar radiation to which corals are exposed. These factors might include cloud cover[46], attenuation in the water column[116], stratospheric ozone[18] and shading by large landforms such as steep-sided shorelines[39].

Natural variations in turbidity may also play an important role in determining bleaching risk. A recent study of the patterns in underwater light levels on a coastal coral reef found that there were periodic intervals of low light levels due to cloud cover and sediment re-suspension (high turbidity), which were driven by large-scale pressure systems[117]. Such natural variability has strong implications for bleaching risk, and knowledge of these factors can be used to prioritise management effort to other factors that are amenable to management intervention.

4.2 Factors that confer resilience to coral bleaching

Resilience to bleaching is determined by the outcome of three key aspects of the bleaching process: resistance to bleaching, ability to survive the bleached state (tolerance) and rate of reef recovery after coral mortality. Understanding the factors that influence each of these steps is central to our ability to understand, and potentially manage, the factors that confer resilience to bleaching on corals.

Understanding the factors that determine variation in bleaching response of corals exposed to temperature stress provides an important basis for management actions in responding to the threat of bleaching

4.2.1 Factors that influence resistance

The variability that characterises bleaching events points to an important fact: individual corals vary in their responses to heat and light stress. Variability in bleaching response has been observed within individual coral colonies, among colonies of the same species, and between colonies of different species[23,118]. These taxonomic variations are further compounded by spatial patterns, with corals of the same species often showing different bleaching responses at different locations[18, 19, 79, 118]. These patterns have been observed at scales ranging from metres to thousands of kilometres. Knowledge of the factors, both external and intrinsic to individual corals, that determine whether corals bleach is an important basis for management actions in response to the threat of bleaching. Better understanding these factors is the central aim of an integrated research strategy being taken in the US territory of American Samoa as a management response to climate change (case study 9).

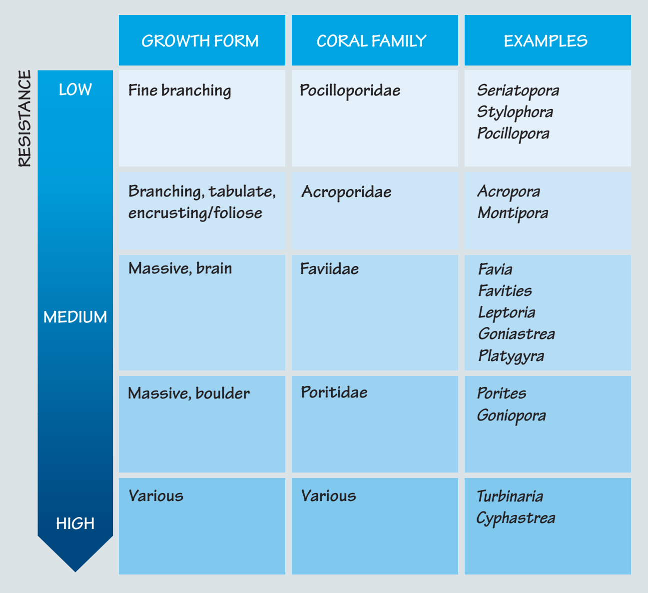
External factors. Externally, there is considerable variation in the environmental conditions experienced by coral colonies. This variation creates critical differences in exposure to heat, light or other stressors, leading to many of the patterns seen in bleaching responses. Some of this patchiness can be attributed to patterns in sea surface temperatures, especially at larger spatial scales[49]. Regional and local differences in weather can also cause differential heating of the water, while proximity to upwelling of cooler waters, mixing by currents and other large-scale processes can help keep temperatures below local bleaching thresholds. At smaller scales, the microenvironment of corals can also vary. Water currents and flow regimes increase water movement around corals, helping them to get rid of metabolic waste and toxic molecules[74], thereby potentially reducing their susceptibility to thermal stress.

Box 4.1 Coral taxa and resistance to mass bleaching

Bleaching resistance is highly variable among corals, as evidenced by the extremely variable responses of coral species to thermal stress. While some corals will show visible signs of bleaching after only one or two weeks at temperatures 1.5°C above the normal maximum, others at the same location will not bleach unless these temperatures persist for more than four to six weeks.

A strong hierarchy of resistance can be detected in diverse coral assemblages, such as those in the western Pacific and Indian Oceans[80] *(Figure 4.1). Typically, fine-structured and fast-growing corals with thin tissue and good connections between polyps tend to be the most susceptible to bleaching. Tissue thickness has been shown to correlate with susceptibility to bleaching*[123, 124]*, although the role and relative importance of these various traits remain to be thoroughly explored.*

Common examples of corals with low resistance are the pocilloporids *and many* acroporids *(especially the branching and tabular growth forms), as well as the hydrocoral* millepora*. Species that are more resistant tend to be characterised by solid, massive skeletons, with thick tissue and slow growth rates, such as* porites, faviids, *and* mussids*. Interestingly, some of the species most often associated with inshore or turbid reef systems are among the most resistant to bleaching, such as* turbinaria[125].



RESISTANCE	GROWTH FORM	CORAL FAMILY	EXAMPLES
LOW	Fine branching	Pocilloporidae	*Seriatopora* *Stylophora* *Pocillopora*
	Branching, tabulate, encrusting/foliose	Acroporidae	*Acropora* *Montipora*
MEDIUM	Massive, brain	Faviidae	*Favia* *Favities* *Leptoria* *Goniastrea* *Platygyra*
	Massive, boulder	Poritidae	*Porites* *Goniopora*
HIGH	Various	Various	*Turbinaria* *Cyphastrea*

Figure 4.1 A generalised hierarchy of coral susceptibility to bleaching
Corals vary in their susceptibility to bleaching. While many factors influence bleaching resistance, the growth form or family of a coral provides a rough but reliable indication of its susceptibility to heat stress.

CASE STUDY 9

An integrated research strategy to assist management responses to climate change – American Samoa

Identifying the need for research

Resource managers increasingly struggle to determine local level responses to climate change. In the US territory of American Samoa, coral reef managers and scientists have identified climate change as a key and imminent threat to the health of the islands' fringing reef system. Physical dangers posed by wave action due to coral loss, increased or decreased rainfall, phase and community shifts on reefs, and sea level rise are just a few of the things that reef managers and policy-makers may have to contend with in coming years at this location. Residents of American Samoa have relied on the reef ecosystem for protection, food, goods and services for millennia. However, they are likely to face severe disruptions to lifestyle, public health hazards, and a decreased ability to be self-supportive if projected increases in the frequency and severity of bleaching eventuate.

In response, local policy-makers are facilitating climate-related research around the islands of American Samoa. It is hoped that data derived from these projects will give managers options for site-specific protection measures, such as Marine Protected Areas, targeted reductions in location-specific land-based sources of pollution, restrictions on use, and even, if appropriate, artificial propagation of coral.


© Chris Hawkins

Ofu Island in American Samoa

Ofu Island – a laboratory in the field

The most notable of the recent research initiatives within American Samoa is being conducted in the lagoonal system along the south shore of Ofu Island. This area is the focus of research aimed at determining whether some of the coral species residing there have adapted to bleaching stresses. The hydrography of the lagoon ensures that there is little, if any, flushing during low tides. It is during these times that temperatures and ultraviolet radiation (UV) around shallow water corals increase dramatically. The extreme temperature ranges that corals in Ofu can withstand on a regular basis indicate that this site may be a natural climate refuge[164.] The warmer water temperatures projected to accompany climate change are likely to result in calmer, clear water (due to stratification and the loss of UV blocking compounds in the water column itself). Knowledge about the characteristics that confer stress resistance to corals of Ofu lagoon can thus be used to understand the features that will help corals survive future thermal stress events in more open reef habitats.

Research projects

Four research projects have been developed by American Samoa in conjunction with various partners. In combination, they will provide valuable insights to guide management efforts aimed at helping American Samoan reefs survive future coral bleaching events.

Are some corals better prepared for climate change? MMA concentrations in Ofu lagoon corals (WWF /Emerald Coast Consulting).

This study examines the microsporine-like amino acid (MAA) concentrations in corals in the lagoons and near-shore (cooler, deeper) reefs of Ofu. Microsporine-like amino acids act as a kind of sunscreen, protecting corals from damaging UV light. Coral nubs are being collected from a combination of species found in all lagoons and paired with samples of the same species from outside of the lagoons, as well as from species only found in some lagoons. These samples will be compared to determine whether their history has imparted some selective advantage in terms of their capacity to deal with the thermal stress associated with future climate scenarios.

Nearshore hydrodynamic modeling for Marine Protected Areas (MPAs) in American Samoa
(Eric Treml and Patrick Halpin, Duke University)

This research uses a spatially explicit, hydrodynamic modelling approach to address high-priority MPA management issues, such as coral bleaching, land-based sources of pollution, and overfishing. The aim is to identify connections among the design of MPAs, long-term monitoring methods and the local needs of American Samoa. Working closely with the local marine management community, this research will result in the development of spatial management strategies and tools for coral reef protection and MPA site development.

Coral disease prevalence on the reefs of American Samoa
(Greta Aeby, Hawaii Department of Land and Natural Resources)

This study addresses issues related to coral disease, coral bleaching and pollution and works to examine the relationships between water quality, coral bleaching and the susceptibility of organisms to disease. The goals of the research are to: (a) conduct a baseline assessment of the abundance and distribution of bleached and diseased corals and of crustose coralline algae at sites throughout American Samoa; (b) correlate the incidence of bleached and diseased colonies with environmental data, and (c) systematically describe gross and microscopic morphology of lesions in corals and crustose coralline algae. This work will help to develop a standardised nomenclature for identifying and classifying diseases. This is a particularly important task as the frequency of disease is expected to increase due to climate change and increases in land-based sources of pollution in reef areas worldwide[27].

Extrinsic and intrinsic factors affecting the resilience of corals to climate change and their use in designing marine reserve networks (Charles Birkeland, University of Hawaii)

This three-year study aims to determine the intrinsic and extrinsic factors that enhance the ability of a diverse set of corals (approximately 100 species) to resist environmental stressors, such as extreme upper temperature limits, temperature fluctuations, and low and high levels of dissolved oxygen. Intrinsic factors include: zooxanthellae types, microbial community composition, microsporine-like amino acid levels and genetic traits. Understanding these factors, and their relevance, will improve knowledge of ecosystem response to environmental factors, and of how future environmental conditions may affect community structure and functions. Such information will ultimately inform managers and scientists designing Marine Protected Areas and similar conservation strategies.

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Other stresses in the external environment of corals can also have an affect on their susceptibility to thermal stress. Preliminary research indicates that synergies between temperature and other stressors, such as pollution, turbidity and sedimentation, changes in salinity or exposure to pathogens, may interact to trigger or exacerbate bleaching[41]. The role of pathogens in localised bleaching may also warrant further consideration, as recent studies have demonstrated the induction of bleaching by bacteria in certain corals from the Mediterranean and Red Seas[119, 120]. Further investigation of these issues, and confirmation of key mechanisms driving synergistic effects involving coral bleaching, have the potential to reveal opportunities for management interventions that could reduce bleaching impacts.

Internal factors. Intrinsically, both the genetic identity and the history of coral colonies and their zooxanthellae can contribute to variation in bleaching susceptibility[23, 121]. This may be observable in individual colonies, or the effect may be observable in the bleaching susceptibility of entire reef communities[122]. At the colony level, species characterised by branching or tabular growth forms and thin or well-connected tissue, tend to bleach more than species with massive growth forms and thicker or less-integrated tissues (see Box 4.1). Thicker tissue may shade zooxanthellae and increase resistance to bleaching[9, 123]. The ranking of common coral groups by bleaching susceptibility is remarkably consistent between sites on opposite sides of the world, suggesting that the properties of the animal host (above and beyond differences in zooxanthellae type) play an important role in determining the response of corals to thermal stress[80].


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Genetic variation among individual zooxanthallae (shown here) influences the resistance of corals to heat stress and bleaching. Although corals may be able to shift the relative dominance of different varieties of zooxanthallae within their tissues in order to increase their resistance to bleaching, there are limits to the extent that corals can use this strategy to acclimatise to large temperature anomalies

The intrinsic characteristics of corals that enable them to adjust to elevated light levels also play a role in determining their resistance to bleaching. Coral polyps that have experienced higher light levels have been shown to be more resistant to bleaching when exposed to high water temperatures[115], suggesting that corals acclimatised to high light will be less likely to bleach in response to thermal stress. This implies that corals that have experienced (and survived) extreme environmental conditions in the recent past may be more resistant to bleaching stress in the future. However, the effects of historical exposure to light are subtle, and acclimatisation is unlikely to allow corals to withstand the large temperature anomalies that have triggered recent mass bleaching episodes[23].

Genetic variation in zooxanthellae is another intrinsic characteristic that could influence the bleaching resistance of corals (Box 4.2). Differences in thermal tolerance among varieties, or clades, of zooxanthellae suggest that coral hosts that have high densities of heat-tolerant algae may be less susceptible to coral bleaching[126]. Shifts toward more heat-tolerant populations of corals or zooxanthellae can be expected to arise from selective mortality of more sensitive genotypes during severe bleaching events. However, corals may also be capable of forming new symbioses with more tolerant zooxanthellae in response to changing temperature regimes (the Adaptive Bleaching Hypothesis)[127]; this possibility remains the focus of ongoing research and discussion (for example, Hoegh-Guldberg et al (2002)[113]).

Box 4.2 Zooxanthellae and resistance to mass bleaching

A characteristic that appears to be important in determining resistance of corals to bleaching is the type of zooxanthellae hosted. Numerous different types, or clades, of zooxanthellae have been recognised, and there is some evidence that they have different susceptibilities to thermal stress[128]. Many corals have multiple varieties of zooxanthellae within their tissue, and the relative proportion of the different varieties is variable. A recent experiment has revealed that some corals can vary the ratio of zooxanthellae clades, with a resulting improvement of their thermal tolerance[129]. This feature is akin to acclimatisation as it involves the use of pre-existing strategies within the coral-zooxanthellae association. If bleaching events increase in both severity and frequency in the future, this may play a small role in determining bleaching response patterns on larger spatial scales. As with other examples of acclimatisation, there is a limit to the extent that corals can use this strategy to shift their thermal tolerance.

Another possible mechanism by which corals could increase their thermal tolerance is to swap their zooxanthellae for more resistant varieties[127]. While this idea continues to be debated[113], it seems increasingly likely that changes in zooxanthellae populations are most likely to occur through shifts in the relative dominance of heat-tolerant varieties already within a coral's tissues, rather than by taking on new varieties. The potential for corals to adopt new varieties of zooxanthellae remains an area of active research.

The role of coral pigments in sheltering zooxanthellae from light stress is another area of active research that could help explain some of the differences in bleaching resistance[110, 111]. Fluorescent pigment granules (FPGs) are common in many corals, at least in the western Pacific. They are positioned within the coral's tissue to optimise the light environment for zooxanthellae, concentrating light in low-light habitats, and shielding zooxanthellae in high light conditions. In this way, corals with high concentrations of FPGs may be less vulnerable to bleaching when water temperatures reach stressful levels.

4.2.2 Factors that influence survival

Bleached corals are still living, and if temperature stress subsides soon enough, most are capable of surviving the bleaching event and repopulating their tissues with zooxanthellae. The mechanism by which corals regain their symbiotic algae probably varies among species. It may occur through uptake of new zooxanthellae from the water column, although the most likely process is multiplication of surviving zooxanthellae that remain in the bleached coral's tissues at very low levels. Even a coral that appears much bleached to the human eye can still retain as many as 100-1000 cells per cm^2 (normal densities are 1-2 x 10^6 per cm^2)[130].

Corals that survive bleaching events are still likely to suffer sub-lethal impacts, such as reduced rates of growth and reproduction and increased susceptibility to diseases

Corals that survive bleaching events can still suffer significant impacts. Reproduction of corals that have bleached and recovered, for example, is much lower than that of corals that have not bleached[26, 114, 131]. Growth of bleached corals is also reduced, probably due to the combined effects of the stress and the reduced supply of energy following decreased zooxanthellae densities[25]. Bleached corals may also have reduced immunity to pathogens, making them more susceptible to disease[27].

The condition, or health, of individual coral colonies is emerging as a particularly important factor in determining whether or not a bleached coral survives. Recent and ongoing studies predict that coral condition (as determined by its energy status or the size of its lipid stores) will affect mortality risk during and following a bleaching event[41]. Specifically, large energy stores are likely to help a coral survive the period of starvation associated with depleted zooxanthellae populations. With adequate energy stores, a healthy coral will be able to maintain itself while bleached, until zooxanthellae populations and photosynthesis can be restored. Similarly, coral species that rely more heavily on heterotrophy (feeding on organic material from the water column) for their energy supply[132], such as those on coastal reefs, are also more likely to be able to tolerate the loss of zooxanthellae.

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Without their energy-providing zooxanthallae, bleached corals essentially enter a period of starvation. The condition of a coral as it enters this state is an important factor determining whether the coral can survive a bleaching-induced 'famine'. Another factor influencing coral survival during bleaching is the coral's ability to feed on plankton and other organic matter in the water column by using its feeding tentacles, as shown here

Box 4.3 How managers can help corals survive bleaching

While extreme temperature stress is almost certain to result in widespread coral mortality, the effects of more moderate temperature anomalies are highly variable. When temperatures do not greatly exceed bleaching thresholds, the coral loses its zooxanthellae, but its tissue may not be directly damaged. Whether mortality follows bleaching in these circumstances is thought to be largely dependent on the coral's ability to endure starvation, or to supplement its energy requirements from food particles captured from the water column (heterotrophy).

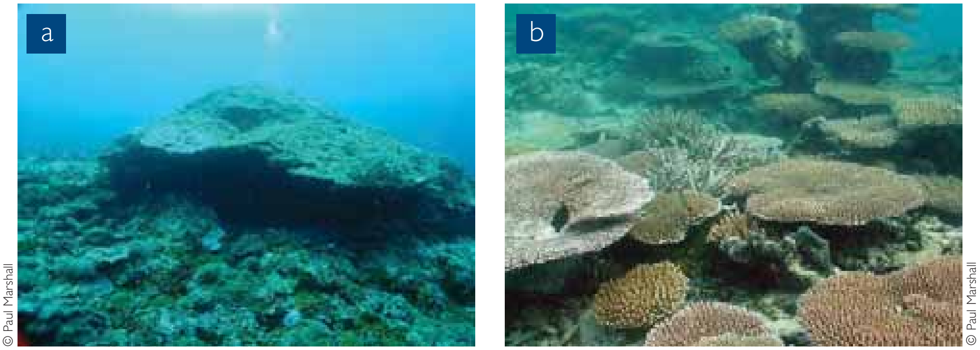
Some corals, especially species adapted to turbid environments, have been shown to rely heavily on heterotrophy. These corals may be less dependent on the energy provided by their zooxanthellae and thus less prone to starvation during a bleaching event. While the importance of heterotrophy to turbid-water corals has been demonstrated[132]*, its role in helping corals to survive bleaching requires further study. A better understanding of this issue may help managers identify coral communities that are at reduced risk of mortality from coral bleaching.*

Coral health prior to exposure to heat stress may be the most important factor influencing colony survivorship during bleaching events. Most corals rely very heavily on the energy provided by their zooxanthellae, and bleaching effectively robs them of their main energy source. As a result, corals in the bleached state are beginning to starve, and their ability to endure this hardship is likely to be important in determining whether they survive. Like many animals, corals store surplus energy as lipids (fats). Corals in good condition will have relatively high lipid levels, endowing them with a buffer against periods of low energy supply. For this reason, it is thought that the condition of a coral at the time it bleaches may play a key role in determining whether it will be able to survive the period of starvation that follows. This implies that chronic stresses, such as water pollution or increased turbidity, which can negatively affect a coral's condition, could increase the risk of corals dying from the acute stress caused by bleaching. While these ideas have only recently begun to be examined for corals[41]*, they suggest that coral health should be considered as a priority focus for reef managers wanting to increase coral survival during moderate coral bleaching events.*

4.2.3 Factors that influence recovery

Significant recovery can occur in only two to three years if mortality is minor (when there is an abundance of colonies that completely or partially survive the bleaching event). However, recovery of coral communities following severe mortality is likely to take much longer[5, 133, 134]. This is because reef recovery is a complex process influenced by multiple, interacting factors. On severely damaged reefs, recovery is dependent on the arrival of suitable coral larvae that have survived the bleaching event elsewhere, and their successful settlement, survival and growth[134]. Even assuming conditions favour recruitment, the recovery process is subject to the vagaries of larval supply and the many risks that confront the young coral, such as predation, smothering by sediments or algae, overgrowth by other corals, etc. In combination, these uncertainties mean that recovery of a site to an abundance, density and diversity of corals comparable to pre-bleaching conditions is a long-term prospect measured in terms of decades[133, 134].

A particularly sensitive step in the recovery process is larval recruitment. The production, settlement and survival of coral larvae is dependent on the availability of 'source' reefs to provide new larvae, good water quality to promote spawning, fertilisation and larval development, and suitable substrate for settlement and survival of coral larvae[45, 134].



Reef recovery after severe coral mortality is a complex process influenced by multiple, interacting factors. These reefs in Palau demonstrate significant differences in their ability to recover. Both were severely affected by mass bleaching in 1998. Seven years after the event, only (a) minimal recovery is evident in one reef, while the (b) other has shown dramatic recovery of coral cover

Degraded water quality can affect the fertilisation success of corals[72, 135, 136], potentially placing severe limitations on the ability of coral communities to recover after bleaching-induced mortality. Water quality can also have a negative impact on recovery by encouraging algal growth, which in turn can reduce larval recruitment[44, 45]. Coral mortality allows an opening for frondose (leaf-like) and filamentous macroalgae ('seaweeds') to take on a more dominant role in reef ecosystems, often at the expense of coral recruitment[42, 45, 137]. This window of opportunity for algae following mortality events such as those associated with severe coral bleaching events means that the influence of nutrients in accelerating growth is more pronounced.

Recovery of severely damaged reefs is dependent on 'source' reefs to provide new larvae, good water quality, and suitable substrate. Where these conditions exist, new corals can settle and become established relatively quickly

The abundance of herbivorous fish populations is another critical factor influencing the success of recovery processes. In situations where herbivores have been heavily depleted through a combination of overfishing and disease, recovery of coral communities following disturbance has been greatly lengthened, or even stalled, resulting in a persistent shift from coral-dominated to algal-dominated reef for over a decade[82, 138].

Recovery can be even further compromised on reefs that are threatened by both degraded water quality and depleted herbivore populations. Increased nutrient levels greatly increase the potential for the excessive growth of algae that can occur when herbivory is reduced. Water quality and herbivore populations are each important, but in combination they become critical in determining the coral-algae balance after a disturbance[42, 45].

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Herbivores, such as grazing fishes, play a key role in maintaining the conditions that are required for the recovery of reefs damaged by coral bleaching

© James Oliver

Algae can overgrow established corals, or inhibit recruitment of new corals, when there are excess nutrients in the system or inadequate levels of herbivory

The importance of local processes highlights the pivotal role that effective management of local stressors can have in supporting the ability of reefs to recover from mortality associated with severe coral bleaching. In keeping with the example above, algal growth and herbivory could be optimised by limiting water pollution and fishing pressure. Furthermore, recent studies suggest that the 'source' of coral recruits is often from within the same or nearby reefs. Together, these insights emphasise the importance of managing local stressors when aiming to support the natural ability of reefs to recover from global stressors like bleaching events[11].

4.3 Can corals adapt to climate change?

The impact of mass coral bleaching on coral reef ecosystems over the long term will depend on the environmental changes that occur in tropical seas, the extent to which corals can acclimatise or adapt to changing conditions, and the ways in which repeat disturbances compound one another to shape coral reef ecosystems.

4.3.1 Future climates

Coral reefs are currently experiencing temperature regimes that exceed any they have experienced over at least the last 400 000 years[28]. Projections of temperature increases suggest that conditions will develop that are vastly different to those in which the majority of coral reefs have developed over the same time frame[11].

Global ocean temperature has increased by an estimated 0.6°C between the mid-1950s and mid-1990s. Some studies predict future increases in global sea temperatures of 1.4-5.8°C by 2100[8], suggesting that mass bleaching events, which may be induced at only 1-2°C above normal summer temperatures, are likely to be a much more frequent phenomenon in the future[9, 13, 28].

Projections of future sea temperature increase suggest that conditions will develop that are vastly different to those in which the majority of coral reefs have developed over the last 400 000 years

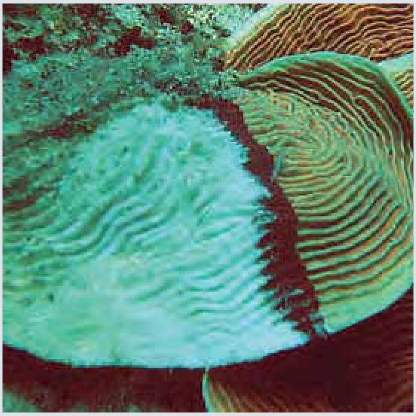
Oceanic currents and atmospheric conditions may also be affected by rising sea temperatures. Changes in the strength and direction of currents are likely to have a strong influence on local temperatures, while changes in atmospheric circulation may influence upwelling, precipitation patterns and the frequency and intensity of regional weather extremes[8]. All of these factors have the potential to increase the extent and severity of mass coral bleaching events. Importantly though, while the potential for these very significant changes is recognised, there remains substantial uncertainty about the direction, magnitude and location of changes in oceanic circulation due to climate change[13].

Potential effects of climate change on coral reefs. Climate change may influence coral reef ecosystems through processes such as mass coral bleaching, changes in the frequency or severity of storms[8], greater virulence of diseases[27], sea level rise[139], and reduced calcification rates in reef-building[20] (see Box 4.4). Of these, mass bleaching events are likely to be the most influential in determining future coral reef condition[13, 28]. By itself, mass bleaching has resulted in significant ecological impacts to coral reef areas unaffected by local stressors. For many other reefs, mass coral bleaching is an additional stress that exacerbates the impacts of local stressors[44]. The influence of mass bleaching events on coral reefs and, in particular, how it interacts with local stressors, will be one of the most important determinants of the future of coral reef ecosystems over the next 50 years[11].

Box 4.4 Coral reefs and climate change: implications beyond mass bleaching

Climate change threatens coral reef ecosystems in other ways aside from increasing the frequency and severity of bleaching impacts. Climate model projections indicate that we can also expect increases in sea level, greater incidence of coral disease and changes in ocean chemistry[13]. While the rates of coral reef growth are likely to keep pace with projections of sea level rise, shoreline inundation with rising water levels pose other risks. Among these are an increase in the export of sediments, nutrients and pollutants from flooded coastal areas. Animals that rely on the low-lying habitat provided by coral reef islands and cays, such as sea turtles and seabirds, are likely to be significantly affected, although these potential impacts are just beginning to be explored.

Many coral diseases increase in virulence at higher temperatures, suggesting greater prevalence of disease outbreaks as average sea temperatures increase. Diseases have already caused chronic coral mortality in many reef areas, such as the Florida Keys and the Caribbean, and reports of coral disease are increasing in other regions including the Great Barrier Reef and other Indo-Pacific locations.



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The impacts of mass coral bleaching will be compounded by other climate-related stressors. In particular, reduced calcification rates and increases in coral disease (shown here) are significant concerns. The incidence of coral disease can be expected to increase because disease virulence increases at higher temperatures and because the incidence of disease has been observed to increase following mass bleaching events, when corals are in a weakened condition

At a regional or global level, changes in ocean chemistry will result from changes in the earth's climate. In particular, dramatic increases in the levels of carbon dioxide (CO^2) in the earth's atmosphere are leading to a reduction in the pH of seawater, which in turn is decreasing the availability of carbonate ions. Reduced calcium carbonate saturation states of seawater are expected to significantly reduce the rates of calcification in key reef-building organisms such as corals and coralline algae[20, 140]. The implications of this for the ability of coral reefs to withstand storms and to maintain their role in shoreline protection are still being examined, but early indications are that these changes will be important, even if they manifest themselves only slowly or subtly. This has particular significance for the ability of coral reefs to maintain their roles in protecting shorelines from oceanic swells and supporting fisheries–both critical ecosystem functions in many tropical regions.

4.3.2 Can corals keep up?

Comparing projected sea temperature increases with existing coral reef temperature thresholds indicates that the frequency and severity of mass bleaching events can be expected to increase significantly. Studies on this issue have concluded that bleaching could become an annual event in coming decades as conditions that are known to have caused major mortality events in the past become more frequent[9, 28, 29]. However, these predictions assume that bleaching thresholds will not change over time, and do not allow for the effect of adaptation. The actual impacts on coral reefs will depend strongly on the capacity of corals to adapt and the rate at which they do so.

Adaptation. There is clear evidence of substantial variation in the resistance and survival of corals to bleaching, raising the possibility that these variations might be attributable to past adaptation. For example, corals of the same species may have a bleaching threshold of 28°C in the Galapagos but be able to tolerate temperatures over 34°C in the Persian Gulf. While these observations suggest that corals have historically had sufficient time and genetic variability to adapt, it is unknown whether they have the capacity to adapt fast enough to keep pace with current rates of change.

Studies that have compared future climate scenarios with current coral bleaching thresholds predict that the frequency and severity of mass bleaching events can be expected to increase significantly

Adaptation involves genetic shifts in populations through selection of more resistant genotypes. This evolutionary process begins as soon as less resistant genotypes are killed. At that point, genotypes that are more resistant begin to make a greater contribution to the next generations of corals. However, the rate of adaptation depends on numerous factors, including the heritability of thermal tolerance, intensity of coral bleaching as a selective process, and the genetic structure of coral populations[11, 23, 28]. While there are differing degrees of optimism among recent studies, there is widespread agreement that the abundance and composition of reef communities will change substantially over coming decades, with large-scale degradation and losses of biodiversity possible in the longer term.

Acclimatisation. Acclimatisation refers to the ability of corals to make biochemical or physiological adjustments that increase their ability to withstand higher sea temperatures[23]. This mechanism occurs at the biochemical or cellular level, usually over time frames of hours or days. Physiological adjustments that give rise to acclimatisation may be highly ephemeral, lasting only as long as the stress, or they may be persistent, endowing a coral with the ability to withstand future stress (such as high temperatures during the following summer). Such adjustments, even short-term ones, usually come with costs, including the diversion of energy away from other processes (such as reproduction). Additionally, for acclimatisation to be effective it must outpace the rate of increases in temperature, which becomes decreasingly likely at the upper level of projected temperature rise.

Incorporation of more heat resistant zooxanthellae within coral tissues is one of the major mechanisms proposed for acclimatisation; however, the extent to which coral species can swap algal symbionts remains unclear. This mechanism, called the Adaptive Bleaching Hypothesis (after Buddemeier and Fautin[127]), proposes that corals may swap their zooxanthellae for a more tolerant type following exposure to sub-lethal thermal stress. This idea is a subject of continuing debate[113, 141].

Corals may also acclimatise to warmer conditions by altering the density or positioning of pigments within their tissue. These pigments, such as fluorescent pigment granules, can shade the zooxanthellae during thermal stress, reducing damage to the photosynthetic system and the risk of bleaching[43, 111]. Enhanced fluorescence seen in some corals that appear to be more resistant to bleaching may be evidence of the role of pigmentation in helping corals acclimatise to thermal stress.

Range-shifts in response to increasing sea temperatures. Coral populations may be able to adjust to increasing temperature regimes through migration of heat-tolerant genotypes. The large differences in the severity of bleaching suffered by corals exposed to otherwise similar conditions strongly suggest that corals differ in their inherent ability to resist bleaching. At least some of the properties that confer thermal tolerance to corals are likely to be heritable (genetically coded). This leads to the potential for larvae from heat-resistant corals to travel to reefs formerly dominated by less hardy genotypes, where they may settle and re-populate areas affected by bleaching-induced mortality. Over time, this could lead to heat-tolerant species or genotypes shifting their range into habitats previously dominated by other species.

The temperature sensitivity of corals, and the likely limitation in their rate of acclimatisation and adaptation, suggests that coral reefs are likely to have less live coral cover and lower biodiversity as a result of a warming climate

The success of this process will depend on the existence and survival of heat-tolerant genotypes, and on connectivity among reefs. In addition, the location and extent of particular thermal realms is not likely to be static as the climate continues to change. This means that range-shifts would need to occur at rates that equal or exceed the rate of movement of thermal realms in order for this process to compensate for the loss of corals due to increasing temperatures.

There have also been suggestions that coral reefs may expand into the subtropics as the temperature warms (see review by Coles and Brown[23]). However, there is a decrease in shallow-water areas and an increase in siliceous sediments further from the equator, creating conditions that are less suitable for reef development. Therefore, although changes in climate may result in more suitable temperatures for coral growth away from the tropics, higher latitude marine environments tend to have substrata that are much less suited to development of carbonate reef structures, resulting in limited potential for reef communities to move towards the poles.

4.4 Reefs and people in the future

There is now abundant evidence that corals are highly sensitive to increases in sea temperature[5, 9, 11, 13, 80]. Their ability to adjust, either through acclimatisation or adaptation, is limited or widely thought to be too slow to keep pace with even conservative climate projections[23, 28]. The implication of these conclusions is that coral reef ecosystems are destined for further change as sea temperatures continue to warm[9, 11, 23]. While there remains great uncertainty about the rate, extent and precise impacts of this deterioration, the future will almost certainly see degradation of reef systems and consequent losses in ecosystem services[9, 13, 23, 31, 37].

4.4.1 Ecological implications

Effects of mass bleaching on coral cover and biodiversity. The temperature sensitivity of corals, and the likely limitation in their rate of acclimatisation and adaptation, suggests that coral reefs are likely to have less live coral cover and lower biodiversity as a result of increases in the frequency and severity of mass bleaching events[11, 23, 28]. Among the coral species most likely to show declines in abundance immediately after a severe bleaching event are those that tend to be relatively fast growing and visually dominant, such as staghorn and tabular *Acropora*[19, 80, 115, 118]. The loss of these species is likely to have a noticeable impact on the aesthetics of many reefs, as well as altering the amount of habitat for many reef-dependent species[11]. While these species may also be among the quickest to recover by way of larval recruitment and rapid growth, it remains highly likely that differences in bleaching susceptibility among corals will result in significant shifts in the community structure of coral reefs. This change is likely to result in flow-on affects to other organisms, as many species, including a variety of fish and invertebrates, are dependent on the habitat provided by branching corals (Box 4.5).

© Paul Marshall

Reefs dominated by corals most sensitive to thermal stress, such as plate and staghorn *Acropora*, are more likely to suffer severe impacts from coral bleaching. Loss of these species is likely to have a noticeable impact on the aesthetics values of reefs as well as the amount of habitat available for many reef-dependent species

© Rohan Arthur

The differential susceptibility of coral species to thermal stress can result in severe shifts in community composition. At this site in the Lakshadweep Islands, India, massive corals such as *Porites* are now the dominant members of the coral community. Prior to the 1998 bleaching event, these sites were dominated by staghorn *Acropora*

Differences in the ability of species to migrate and to adapt will further exacerbate changes in community structure due to differential mortality from severe bleaching. If bleaching events become increasingly frequent, the more susceptible species may have trouble re-establishing between bleaching events, leaving abundant space available for algal growth. Decreasing time intervals between bleaching events would also limit opportunities for resistant species to establish sustainable populations before temperatures increase again. While the exact change to reefs based on projected increases in the frequency and severity of mass bleaching are highly uncertain, recent modelling studies[9, 31, 47] report the possibility of extensive degradation.

Box 4.5 Implications of coral bleaching for reef biodiversity

Our understanding of the impacts of climate change on biodiversity is in its infancy. While the pathway and time course of this change is undefined, most experts agree that biodiversity will be affected to some extent by a rapid loss of reef-building corals resulting from major disturbances such as coral bleaching events. Given the strong relationships that characterise reef ecosystems, many other species are also vulnerable to the impacts of coral bleaching.


© Ove Hoegh-Guldberg

Coral bleaching also has implications for biodiversity. For example, the orange-spotted filefish rapidly disappeared from reefs around Okinawa after the 1998 coral bleaching event

Organisms that depend on corals for food or shelter and which reproduce via external fertilisation may be most threatened by bleaching, with extinction becoming a real risk as the primary habitat provided by corals becomes rarer. The kinds of organisms most at risk include the obligate corallivores: those species that eat only corals. These species are directly dependent on the presence of coral for their existence and disappear quickly if coral is removed. The orange-spotted filefish (Oxymonacanthus longirostris) is an example; it rapidly disappeared from reefs around Okinawa after the 1998 bleaching event[142].

The response of the broader coral reef fish community to bleaching-induced losses of corals has proven more complex. Declines in some species (especially damselfishes that are strongly associated with branching corals) have been recorded following bleaching[63, 64, 143]*. In one recent study*[143]*, over 75 per cent of reef fish species declined in abundance, and 50 per cent declined to less than half their original numbers, following a devastating decline in coral cover caused in part by coral bleaching. However, the overall structure of fish communities in the Seychelles changed very little despite massive (threefold-twentyfold) decreases in live coral cover after the 1997-98 bleaching event*[64]*. Abundances of some fish have even appeared to increase following the loss of reef-building corals, with an overall increase in fish abundance observed after the 1998 mass bleaching event on Tanzanian reef systems*[63]*. These increases in fish populations appear to be caused by increases in herbivorous fishes, which may be responding to the greater availability of algae following reductions in coral cover.*

Other organisms are also likely to respond to changes in coral cover. For example, over 55 species of decapod crustaceans are associated with living colonies of a single coral species, Pocillopora damicornis[144, 145]*. Nine of these are known to be completely dependant on living pocilloporid coral colonies. Similarly, branching corals of the genus* Acropora *have 20 species that depend solely on the habitat they provide.*

Even under relatively conservative projections of sea temperature warming, many reefs previously dominated by a diverse assemblage of hard corals may give way to low-diversity, low-cover reef communities, reducing the ecosystem services upon which humans depend

Prospects for future coral reef condition. Even under relatively conservative projections, many reefs previously dominated by a diverse assemblage of hard corals may give way to low-diversity, low-cover reef communities. In the extreme, this may lead to algal-dominated reefs with low habitat complexity and limited scope for recovery by hard corals, all within 50 years. Although these projections may sound severe, they do not rely on catastrophic change. Rather, they assume, very conservatively, that reefs can recover between bleaching events as long as there are fewer than three massive mortality events per decade[28, 29]. Additionally, these projections do not consider the cumulative or synergistic effects of other stresses, such as water pollution or destructive fishing practices.

Reef recovery between mass bleaching events may be impeded by several factors (see Section 4.2.3 for information about factors that support reef recovery). Recovery processes can be substantially hindered by erosion of reef structures following coral mortality. The grazing of sea urchins in very high densities has led to erosion of reef structures in eastern Pacific reefs, such that the degraded state of reefs has persisted for two decades after the mass bleaching event of 1983[146, 147]. Projected reductions in the pH of upper ocean waters are likely to further encourage both biological and chemical erosion of reefs. Severe erosion can also lead to a shift toward an unstable substrate of coral rubble, making recovery from bleaching-induced coral mortality difficult[106]. The evidence from past mass bleaching events is that, while there are reports of active recovery from some sites, in general damaged reefs remain degraded compared to their pre-bleaching condition. It seems likely that the impacts of bleaching-induced mortality are likely to be evident for at least a decade at many locations.

While coral reefs are unlikely to be eliminated globally because of mass bleaching events, predicted declines in reef condition have serious implications. Reduced coral cover and degraded community structures are expected to reduce the suitability of coral reefs as habitat for many species, impacting the biodiversity and ecosystem services upon which humans depend. Although knowledge of the inter-dependencies is only beginning to accumulate, managers are becoming increasingly concerned about the effects of deterioration in reef condition on the human communities and industries that have come to rely on healthy ecosystems for their livelihood and lifestyle.

4.4.2 Social and economic implications

Impacts on fisheries. Changes in coral reef ecosystems resulting from bleaching are expected to translate into shifts in fish species composition and, possibly, reduced fishery catches[59, 148-151]. Coral reef ecosystems support fisheries by providing food and habitat for a diversity of species. Coral mortality from mass bleaching events leads to loss of reef structure and habitat, as dead coral skeletons erode and break down. This deterioration of the reef structure is probably not much different in nature from that caused by other disturbances, such as coral disease or outbreaks of the coral-feeding sea star *Acanthaster plancii*. However, the effects of coral bleaching events can extend over hundreds or thousands of kilometres[152], causing stress or damage on scales not normally experienced by coral reef ecosystems. Where significant coral mortality occurs, coral bleaching can result in dramatic decreases in the amount of habitat available for fish and other mobile reef species that depend on the structure provided by healthy coral reefs[64, 143].

© Simon Albert

Changes in coral reef ecosystems caused by coral bleaching are expected to affect fisheries, especially small-scale and subsistence fisheries

Strongly coral-dependent fish species are expected to be the most affected by bleaching-induced coral mortality. Several species of fish are reliant on coral as a primary food source, and many other species use coral for shelter from predators. Post-bleaching declines in populations were recorded following the 1997-98 mass bleaching episode for several fish species that feed exclusively on corals[64, 142, 153], as well as for those that rely on coral for habitat, such as species of damselfishes that are strongly associated with branching corals[63, 64].

© Yusri Yusuf

Fish species that are strongly dependant on corals for habitat or food, such as this damselfish on a reef at Pulau Pemanggil, Malaysia, are expected to be the most affected by bleaching-induced coral mortality. These coral-dependent fishes are important prey for larger species, many of which are targeted in coral reef fisheries

Coral-dependent fishes are important prey for larger species, many of which are targeted in coral reef fisheries. Bleaching events that result in widespread loss of physical habitat would be expected to have 'flow-on' effects for the higher trophic level predator fishes often targeted. Yet, while impacts on fish populations of the 1997-98 mass bleaching event have been clearly documented in several locations, evidence of impacts on fishery yields and income has been more difficult to document[44, 148, 154.] This may indicate that: (1) the expected relationship between loss of coral cover and predatory fish abundance is too simplistic; (2) functional redundancy at the study sites is, in the short-term, masking the likely impacts on higher-level predators in the long-term or (3) the relationship between fishers and the fishery resources are more dynamic and complex than expected (or a combination of these three factors).

© James Oliver

Coral reef-based fisheries are the major source of food and income for coastal communities of tropical regions worldwide

Many reef-based fisheries are generalist in that they target a wide variety of species and sizes, and are partly subsistence-based. These characteristics make many reef-based fisheries both adaptable to changing conditions and able to be influenced by other external factors. Consequently, single cause-effect linkages may be difficult to discern. While the dynamic and adaptive nature of reef-based fisheries may make them more resilient to short-term decreases in fish stocks, they may also obscure indications of long-term risks to the sustainability of the fishery (see Section 2.4).

Impacts on tourism. Changes in coral reef ecosystems resulting from bleaching are expected to translate into economic losses to the tourism industry. The extent of the impact on tourism businesses varies with the flexibility of individual markets. For example, dive businesses that are based in population centres are likely to be more capable of responding to changes in reef quality caused by mass bleaching, because they may be able to shift from a focus on providing high quality dive sites for experienced divers to new divers expecting instruction or even to non-divers. By comparison, mass bleaching may significantly affect businesses based on taking divers to remote locations that are renowned for exceptional coral reef quality, but where options for business diversification are limited.

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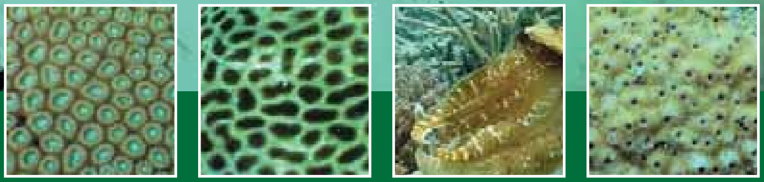
Reef-based tourism plays a key role in many regional and national economies. Small-scale reef-oriented businesses, such as this ecotourism venture in the Philippines are vulnerable to deterioration in reef condition resulting from coral bleaching. Tourism businesses based on taking divers to remote locations renowned for exceptional coral reef quality are more likely to be negatively impacted by mass bleaching than operators based in population centres that may have more options for business diversification

Several recent studies have attempted to quantify losses resulting from coral bleaching on reef-based tourism industries. Estimates of the welfare loss between 1998-2001 from the 1997-98 mass bleaching event in Zanzibar, Mombasa, and the Seychelles are US$5.4 million, $6.4 million, and $9.7 million, respectively[37]. A recent study in Australia has estimated potential losses of US$95.5 million to US$293.5 million to the tourism industry by 2020 as a result of predicted deterioration in reef condition caused by coral bleaching[28].



CHAPTER 5

ENABLING MANAGEMENT – A POLICY REVIEW

5. ENABLING MANAGEMENT – A POLICY REVIEW

Implementing management measures for mass bleaching will require a mandate from decision-makers as well as additional resources

This guide has aimed to identify and describe actions that managers can take in response to mass coral bleaching events. However, in almost all cases, implementing these ideas will require a mandate from decision-makers as well as additional resources. Clear policies that articulate the need for, and value of, managing reefs in the context of an increased frequency of mass bleaching events will raise the profile of this issue, and so assist management. Ultimately, management for mass bleaching will require that the demand for these activities be reflected in national and local policies and resource budgets.

Currently, there are three policy areas of mass bleaching research and discussion: coral reefs, climate science, and biological diversity. Over the last five years, all three have demonstrated two trends: (1) recognition of a need for research followed by recognition of a need for management and (2) a call for international action followed by a call for national action and, in some cases, local action. These trends are positive signs for managers wanting support to implement the activities in this guide. This section reviews international policy related to mass coral bleaching, and provides information on the types of mandates that currently support management for mass bleaching.

5.1 Coral reefs

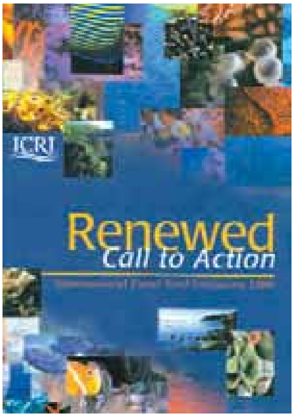
Through the International Coral Reef Initiative (ICRI), three important policy statements have called for international action in relation to mass coral bleaching events and climate change (www.icriforum.org). Initiated in 1995, ICRI is a partnership among nations and organisations authorised to implement Chapter 17 of Agenda 21 (adopted at the Earth Summit, 1992) and other international agreements relevant to the conservation and management of coral reefs.

In 1995, ICRI issued a 'Call to Action' that identified as one of four key threats to coral reefs 'the potential adverse effects of climate change, including temperature and sea-level changes, alteration of natural patterns of precipitation, tropical storms and ocean circulation'. Three years later, recognition of mass bleaching as a major threat to coral reefs had become much stronger. An ICRI-sponsored event, the International Tropical Marine Ecosystem Management Symposium (ITMEMS), issued a 'Statement on Coral Bleaching' that noted the severity of the 1997-98 event, observing that resulting coral mortality reached as high as 90 per cent in some areas. The statement expressed concern that projected increases in temperature are likely to lead to an increase in the frequency of coral bleaching events and associated ecological and socioeconomic consequences. The statement identified a need for cross-disciplinary research and, specifically, establishment of 'a multi-disciplinary taskforce…to thoroughly inform the IPCC [Intergovernmental Panel on Climate Change] on coral reef issues prior to their next report due in 2001'.

By 2003, ITMEMS 2 recognised the need and ability to manage reefs for mass coral bleaching. The conference statement concluded that 'coral reefs of the world have been deteriorating from coral bleaching and mortality due to warming seas' and that managers can 'address these trends by adopting a number of risk minimising strategies'. The statement recommends six strategies, summarised as:

- support resilience by managing threats within management control
- factor risk of bleaching impacts into representative MPA networks
- incorporate flexibility to respond to mass bleaching into coral reef management plans
- influence policy related to climate change
- document and raise awareness about bleaching impacts
- promote documentation and mitigation of other negative effects of climate change on tropical marine species and ecosystems, including turtles, seabirds, mangroves, etc.

ICRI policy statements have been effective in catalysing national and local coral reef management around the world. In response to recommendations in the 1995 Call to Action, many countries have developed national coral reef initiatives, including Indonesia, the Philippines, Thailand, the United States, Mexico, and Netherlands Antilles. Furthermore, the International Coral Reef Action Network (ICRAN) was formed as an action-oriented response and partnership to ICRI's call. ICRAN continues to work to halt the global decline in the health of coral reefs.



In 1998, the coral reef management community, through ICRI, issued a "Statement on Coral Bleaching" in its *Renewed Call to Action* (shown here) that raised concern about mass bleaching and called for research to evaluate its consequences. By 2003, that call went further by recognizing both the need and the ability to manage coral reefs for mass bleaching, in a conference statement adopted at ITMEMS 2. Several policy forums related to mass bleaching demonstrate this trend–of moving from a call for research to a call for management. They also move from a call for international action to a call for national action, and sometimes, local action.

In the United States, efforts originating from the 1995 ICRI Call to Action have resulted in national policies calling for management of mass coral bleaching, even at the local level (www.coralreef.gov). In 2000, the US National Action Plan for Coral Reef Conservation called for increased research and monitoring to strengthen understanding of and response to mass bleaching events. Two years later, the US Coral Reef Task Force passed two resolutions calling for the incorporation of mass bleaching events into management policy. The first called for a public-private partnership to comprehensively address research into and management of bleaching-related impacts to reefs. The second called on individual US states and territories, with their federal partners, to develop local action strategies for responding to key threats to reefs, including climate change and coral bleaching. While it is too soon to judge the success of these initiatives, such local level approaches to managing mass bleaching may be well-suited to other decentralised coral reef management regimes, such as those of Indonesia and the Philippines.

5.2 Climate science

Unlike coral reef policy, climate science forums do not issue prescriptive policies. However, they do aim to be policy relevant, and the technical synthesis documents they produce are important for establishing the accepted state of knowledge and describing priority knowledge gaps in existing information. Several important climate science documents have issued findings that articulate the importance of mass bleaching as a serious threat to coral reefs, the links between increased sea temperatures and mass bleaching, and the priority for additional research into coral reef management options in the face of climate change.

In its third assessment (2001), the Intergovernmental Panel on Climate Change (IPCC) identified coral reefs as one of the natural systems especially vulnerable to climate change. This suggests that coral reefs are among the ecosystems that, due to their limited adaptive capacity, may undergo significant and irreversible damage because of climate change. The assessment considered what type of climate-related impacts will most affect reefs, finding that increases in the frequency of extreme temperature events and consequent bleaching events, and changing CO_2 levels that reduce the rate of reef calcification will be more significant than impacts associated with sea-level rise. Quoting several studies, the IPCC Working Group II technical review noted, 'rising SST [sea surface temperature] will create progressively more hostile conditions for many reefs. This effect, along with decreased $CaCO_3$ saturation state, represents two of the most serious threats to reefs in the 21st century'.

The Strategic Plan for the US Climate Change Science Program is similar to the IPCC in recognising coral reefs as particularly vulnerable, and calling for research to strengthen coral reef management options. The plan indicates that, while bleaching events prior to the 1980s were generally attributed to local phenomena, a direct relationship between bleaching events and elevated ocean temperature has since been found (US Climate Change Science Program, 2003). The plan emphasises that management practices can be used to sustain ecologically related goods and services. Specifically, it identifies as a priority research question: 'How can coral reefs be managed for tourism, erosion protection, and biodiversity, considering potential global changes?'. Research needs listed under this question include assessments of the direct and indirect ecological effects and economic costs of management practices through regular monitoring, evaluation, and experimentation–the overarching goal being to enable adaptive shifts in management.

5.3 Biological diversity

The Convention on Biological Diversity (CBD) has called for management, research, capacity building and financing of activities that address mass coral bleaching. Additionally, the CBD has catalysed national efforts to consider climate change-related impacts on biodiversity. One example of such an effort is Australia's Biodiversity and Climate Change Action Plan, which includes sections on the mass coral bleaching issue.

In 1998, the CBD formed a Subsidiary Body on Scientific, Technical and Technological Advice (SBSTTA) for assistance in developing policies on mass coral bleaching. After issuing initial findings in an Expert's Meeting report, a Specific Work Plan on Coral Bleaching was developed (www.biodiv.org). Recommended actions in the first work plan included targeted research, monitoring and assessment, stakeholder engagement, the development of case studies, technical capacity, and Integrated Coastal Management (ICM) plans. The work plan also called for increased recognition of coral bleaching in related international conventions and the mobilisation of financial and technical assistance to address the issue.

At the 2004 CBD Conference of Parties, the Specific Work Plan on Coral Bleaching was updated, adding a category for 'Management Actions and Strategies'. Recommended management actions included: (a) identification and management of areas of demonstrated resilience; (b) assistance for focused management activities; (c) development of pilot projects for management interventions to increase short- and long-term reef resilience; (d) integration of resilience principles into MPA design and (e) increased efforts to reduce localised stressors to promote resilience. Management concepts were also integrated into the other sections during the 2004 update, including a recommendation to support training managers in the tools necessary to respond to mass bleaching events.

Countries that are signatories to the CBD are to complete national level assessments of biological diversity. In Australia, a partnership of federal and state governments has recently completed a National Biodiversity and Climate Change Action Plan (NBCCAP) that specifically calls for management efforts to minimise the impacts of coral bleaching events. This plan calls for the integration of climate change concerns into standard management operations, and includes research, communication, and management components. The section on marine and coastal ecosystems recommends:

- building capacity to predict the effects of climate change on coastal and marine ecosystems in ecological and socioeconomic terms
- identifying and implementing strategies that minimise the impacts of climate change on vulnerable coastal and marine ecosystems and, particularly, for acute impacts from climate change, such as coral bleaching
- maximising the resilience of coastal and marine ecosystems to climate change
- considering the impacts of climate change when selecting new Marine Protected Areas.

International policy forums related to coral reefs, climate science, and biological diversity have all recognised the need for management action to respond to mass coral bleaching. These international statements offer support to managers who want to implement the strategies described in this guide

Summary. Many countries with coral reefs are participants in ICRI, signatories to the CBD, and involved with the IPCC. Policies and statements issued in these international forums may help managers develop the political will and acquire the resources to implement their own plans to respond to mass bleaching events and to build coral reef resilience. As discussed here, there are already examples of the ways these international policies can and have influenced the development of policies that incorporate mass coral bleaching into management at both national and local levels. *A Reef Manager's Guide to Coral Bleaching* is intended to provide the knowledge and tools that will enable managers to take the actions required by these policy initiatives.

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GLOSSARY OF TERMS

Note that many of these definitions are in a coral bleaching or climate change context, and that more general definitions may apply in other fields.

Biodiversity The numbers and relative abundances of different genes (genetic diversity), species, and ecosystems (biological communities) in a particular area.

Climate Climate in a narrow sense is usually defined as the 'average weather,' or more rigorously, as the statistical description in terms of the mean and variability of relevant quantities over a period of time ranging from months to thousands of years. The classical period is 30 years, as defined by the World Meteorological Organisation (WMO). These quantities are most often surface variables such as temperature, precipitation, and wind. Climate in a wider sense is the state, including a statistical description, of the climate system.

Climate change Climate change refers to any change in climate over time, whether due to natural variability or as a result of human activity. This usage differs from that in the United Nations Framework Convention on Climate Change (UNFCCC), which defines 'climate change' as: 'a change of climate which is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and which is in addition to natural climate variability observed over comparable time periods'. See also *climate variability*.

Climate variability Climate variability refers to variations in the mean state and other statistics (such as standard deviations, the occurrence of extremes, etc.) of the climate on all temporal and spatial scales beyond that of individual weather events. Variability may be due to natural internal processes within the climate system (internal variability), or to variations in natural or anthropogenic external forcing (external variability). See also *climate change*.

Coral bleaching The paling of corals resulting from a loss of symbiotic algae. Bleaching occurs in response to physiological shock in response to abrupt changes in temperatures, salinity and turbidity (also see Mass coral bleaching).

Coral reef A marine ridge or mound that has been built up over thousands of years from limestone (calcium carbonate) deposited in the skeletons of coral polyps. The term coral reef is often used to refer to the entire ecosystem: the coral, the substrate built by the coral and the organisms that live in, on and around the reef. The geographical shape of a reef can also be part of the definition: fringing reefs, barrier reefs and atolls.

Diurnal temperature range This is the difference between the daily maximum and minimum temperatures, which has been observed to be decreasing globally, especially in Australia.

ENSO El Niño Southern Oscillation (ENSO) refers to widespread 2-7 year oscillations in atmospheric pressure, ocean temperatures and rainfall associated with El Niño (the warming of the oceans in the equatorial eastern and central Pacific) and its opposite, La Niña. Over much of Australia, La Niña brings above average rain, and El Niño brings drought. A common measure of ENSO is the Southern Oscillation Index (SOI) which is the normalised mean sea level pressure difference between Tahiti and Darwin. The SOI is positive during La Niña events and negative during El Niño events.

Eutrophication The increase in dissolved nutrients and decrease in dissolved oxygen in a (usually shallow) body of water, caused by either natural processes or pollution.

Global temperature Usually referring to the surface temperature, this is an area-weighted average of temperatures recorded at ground- and sea-surface-based observation sites around the globe, supplemented by satellite-based or modelbased records in remote regions.

Global warming An increase in global average surface temperature due to natural or anthropogenic climate change.

Integrated coastal management (ICM) A continuous and dynamic process by which decisions are made for the sustainable use, development, and protection of coastal and marine areas and resources. The process is designed to overcome the fragmentation inherent in both the sectoral management approach and splits in jurisdiction among levels of government at the land-water interface. This is done by ensuring that the decisions of all sectors and all levels of government are harmonized and consistent with the coastal policies of the nation in question. A key part of ICM is the design of institutional processes to accomplish this harmonization in a politically acceptable manner. See 'Integrated Coastal and Ocean Management: Concepts and Practices' by B. Cicin-Sain and R. Knecht (1998).

IPCC The Intergovernmental Panel on Climate Change, set up in 1988 by the World Meteorological Organisation and the United Nations Environment Program to advise governments on the latest science of climate change, its impacts and possible adaptation and mitigation. It involves panels of climate and other relevant experts who write relevant reviews, which are then critically reviewed by many other researchers and governments from member countries around the world. Summaries for Policymakers are adopted in a plenary session of government delegates, typically from over 100 member countries including developed and developing countries. See www.unep.ch/ipcc.

Marine Protected Area Any area of the intertidal or subtidal terrain, together with its overlying water and associated flora, fauna, historical and cultural features, which has been reserved by law or other effective means to protect part or all of the enclosed environment.

Mass coral bleaching Coral bleaching extending over large distances (often affecting reef systems spanning tens to hundreds of kilometres) as a result of anomalously high water temperatures.

Mitigation Mitigation of climate change refers to those response strategies that reduce the sources of greenhouse gases or enhance their sinks, to subsequently reduce the probability of reaching a given level of climate change. Mitigation reduces the likelihood of exceeding the adaptive capacity of natural systems and human societies.

Photosynthesis The production of chemical compounds in the chlorophyll containing tissues of plants, in particular the formation of carbohydrates from the carbon in carbon dioxide and the hydrogen in water with the aid of sunlight, releasing oxygen in the process.

Predictions A prediction is a statement that something will happen in the future, based on known conditions at the time the prediction is made, and assumptions as to the physical or other processes that will lead to change. Because present conditions are often not known precisely, and the processes affecting the future are not perfectly understood, such predictions are seldom certain, and are often best expressed as probabilities. Daily weather forecasts are 'predictions' in this sense: they are predictions of what the weather will be like, but have uncertainties due to inexact observations and weather models. They are often expressed in probabilistic terms.

Projection Projections are sets of future conditions, or consequences, derived on the basis of explicit assumptions, such as scenarios. Even for a given scenario or set of assumptions, projections introduce further uncertainties due to the use of inexact rules or 'models' connecting the scenario conditions to the projected outcomes.

Protected Area An area of land and/or sea especially dedicated to the protection of biological diversity, and of natural and associated cultural resources, and managed through legal or other effective means.

Risk Risk is the probability that a situation will produce harm under specified conditions. It is a combination of two factors: the probability that an adverse event will occur; and the consequences of the adverse event. Risk encompasses impacts on human and natural systems, and arises from exposure and hazard. Hazard is determined by whether a particular situation or event has the potential to cause harmful effects.

Scenario A climate scenario is a coherent, internally consistent and plausible description of a possible future state of the climate. Similarly, an emissions scenario is a possible storyline regarding future emissions of greenhouse gases. Scenarios are used to investigate the potential impacts of climate change: emissions scenarios serve as input to climate models; climate scenarios serve as input to impact assessments.

Sensitivity The degree to which a system is affected, either adversely or beneficially, by climate related stimuli, including mean (average) climate characteristics, climate variability and the frequency and magnitude of extremes.

Sustainability Sustainable activities meet the needs of the present without having a negative impact on future generations. A concept associated with sustainability is triple bottom line accounting, taking into account environmental and social costs as well as economic costs.

Threshold Any level of a property of a natural or socioeconomic system beyond which a defined or marked change occurs. Gradual climate change may force a system beyond such a threshold. Biophysical thresholds represent a distinct change in conditions, such as the drying of a wetland, floods, or breeding events. Climatic thresholds include frost, snow and monsoon onset. Ecological thresholds include breeding events, local to global extinction or the removal of specific conditions for survival. Socioeconomic thresholds are set by benchmarking a level of performance. Exceeding a socioeconomic threshold results in a change of legal, regulatory, economic, or cultural behaviour. Examples of agricultural thresholds include the yield per unit area of a crop in weight, volume or gross income. See also *critical thresholds*.

Uncertainty The degree to which a value is unknown, expressed quantitatively (for example, a range of temperatures calculated by different models) or qualitatively (for example, the judgement by a team of experts on the likelihood of a collapse of the *West Antarctic Ice Sheet*. Uncertainty in climate projections is primarily introduced by the range of projections of human behaviour which determine emissions of greenhouse gases, and the range of results from *climate models* for any given greenhouse gas.

Vulnerability The extent to which a natural system or human society is unable to cope with the negative impacts of climate change, variability and extremes. It depends on changes in climate as well as the sensitivity and adaptive capacity of the system or society.

Zooxanthellae Microscopic single-celled algae (usually dinoflagellates) that form symbiotic relationships with corals, sea anemones, molluscs and several other types of marine invertebrates.

ACRONYM LIST

AIMS	Australian Institute of Marine Science
CBD	Convention on Biological Diversity
CDOM	coloured dissolved organic matter
CORDIO	Coral Reef Degradation in the Indian Ocean
COTS	crown-of-thorns starfish
CRW	Coral Reef Watch
CSIRO	Commonwealth Scientific and Industrial Research Organisation (Australia)
DHW	degree heating weeks
ENSO	El Niño-Southern Oscillation
FKNMS	Florida Keys National Marine Sanctuary
GBR	Great Barrier Reef
GBRMPA	Great Barrier Reef Marine Park Authority
GCRMN	Global Coral Reef Monitoring Network
ICLARM	International Centre for Living Aquatic Resources Management (now WorldFish Centre)
ICM	integrated coastal management
ICRAN	International Coral Reef Action Network
ICRI	International Coral Reef Initiative
IPCC	Intergovernmental Panel on Climate Change
ITMEMS	International Tropical Marine Ecosystem Management Symposium
IUCN	IUCN - The World Conservation Union
KEYS	Keep your Eyes on the Reef program
KMR	Kiunga Marine Reserve
KWS	Kenya Wildlife Service
LIT	line intercept transects
MAA	microsporine-like amino acid
MPA	Marine Protected Area
NBCCAP	National Biodiversity and Climate Change Action Plan
NGO	non-governmental organisation
NOAA	US National Oceanographic and Atmospheric Administration
SBSTTA	Subsidiary Body on Scientific, Technical and Technological Advice
SEYMEMP	Seychelles Marine Ecosystem Management Project
SST	sea surface temperature
TNC	The Nature Conservancy
WCS	Wildlife Conservation Society
WTP	willingness to pay
WWF	World Wildlife Fund

GREAT BARRIER REEF CORAL BLEACHING RESPONSE PLAN

APPENDIX

INTRODUCTION

Large-scale coral bleaching events, driven by unusually warm sea temperatures, have now affected every major coral reef ecosystem on the planet (Wilkinson 2004). The effects of coral bleaching are pervasive and potentially devastating to ecosystems and the people and industries that depend upon them. The frequency and severity of these large-scale disturbances is predicted to increase as temperatures continue to warm under a global regime of climate change. Climate change, in combination with the multitude of other stressors resulting from human activities is leading to unprecedented pressure on coral reefs. Understanding the effects and implications of coral bleaching and identifying strategies to reduce stress and mitigate impacts are urgent challenges for the conservation and management of coral reefs worldwide.

The Great Barrier Reef Marine Park has experienced two major coral bleaching events in recent years: 1998 and 2002. The spatial extent of these events, combined with the high level of mortality seen at severely affected sites, has lead to widespread concern about the future of the Great Barrier Reef in the face of global climate change. The Great Barrier Reef Marine Park Authority's (GBRMPA) Coral Bleaching Response Plan has been developed to provide an early warning system for conditions that are conducive to coral bleaching, and to document the extent and severity of coral bleaching events using broad-scale synoptic surveys and ecological surveys. The information collected under this Response Plan can be used to compare and analyse the frequency and patterns of bleaching events and to develop forecasting tools.

1. Plan Overview

This document describes a Coral Bleaching Response Plan for the Great Barrier Reef (GBR). This will enable GBRMPA to:

- develop a system to forecast coral bleaching events;
- provide early warnings of a major coral bleaching event;
- measure the spatial extent and severity of mass coral bleaching events;
- assess the ecological impacts of mass coral bleaching events;
- involve the community in monitoring the health of the GBR;
- communicate and raise awareness about coral bleaching and climate change impacts on the GBR; and
- provide information to evaluate the implications of coral bleaching events for management policy and strategies.

The Great Barrier Reef Coral Bleaching Response Plan (the Response Plan) has been developed in conjunction with 'A Global Protocol for Assessment and Monitoring of Coral Bleaching' (WWF, FishBase and GBRMPA), and 'A Reef Manager's Guide to Coral Bleaching' (an international collaborative effort led by the US Coral Reef Task Force and GBRMPA).

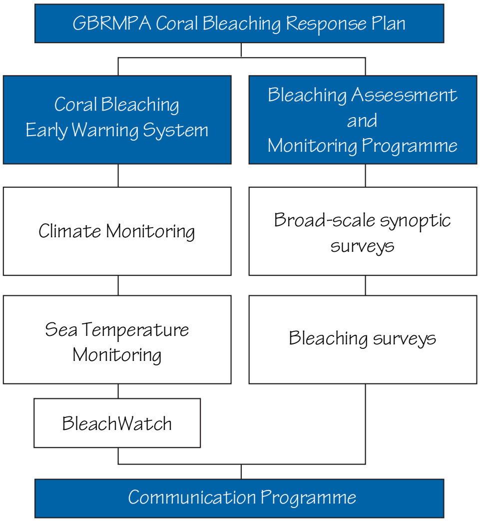
It aims to maximise comparability and consistency with bleaching response plans in other regions. The Response Plan also links in with GBR tourism industry-based monitoring programs such as 'Eye on the Reef'.

The GBR Coral Bleaching Response Plan has the following three main components (Figure 1):

- Early Warning System
- Bleaching Assessment and Monitoring
- Communication Programme

The following sections detail the rationale, strategies and methods for each of the components. The final section of the Response Plan includes a detailed description of the implementation plan.

Figure 1. Schematic overview of GBR Coral Bleaching Response Plan elements



1.1 Selecting Appropriate Coral Bleaching Monitoring for the GBR

A Global Protocol for Assessment and Monitoring of Coral Bleaching outlines a range of monitoring activities that can be conducted to address the objectives of a coral bleaching monitoring plan. The broad objectives of the GBR Coral Bleaching Response Plan are to document and assess:

1. The extent and severity of coral bleaching (if an event occurs)
2. The duration of a coral bleaching event
3. The ecological impacts of a coral bleaching event
    a. Does bleaching result in changes to species diversity and/or coral cover?
    b. Does bleaching result in changes to relative abundance and dominance of different species?
    c. Does bleaching result in changes to reef structure and habitat complexity, for example are there impacts on other species?
    d. Does bleaching result in changes to the ability of reefs to recover after an impact?
4. Other anthropogenic stresses that may affect the severity of coral bleaching and recovery

The GBR Coral Bleaching Response Plan also expects to provide a foundation to develop an understanding of the social and economic impacts of coral bleaching.
Table 1 from the *Global Protocol* provides a guide to the types and frequency of monitoring that should be considered for different resource scenarios and for different objectives. The GBRMPA Climate Change Response Team reviewed the needs of the Response Plan and designed the monitoring plan using the following selected methods based on the available resources.

Table 1. Monitoring activities of the GBR Coral Bleaching Response Plan

Question	Resource scenarios		
	1. Low	2. Medium	3. High
A. What is the general extent and severity of the current bleaching event?	A1 • Circulate questionnaires (BleachWatch) amongst local divers and other reef users. • Submit information to ReefBase.	A2 • Identify major species affected (take photos or video footage).	A3 • Conduct detailed surveys of representative sites using transects and a precise measure of percentage of coral affected (line transect, video-transect). • Use remote sensing to obtain synoptic estimates over wider geographic area.
B. Is the bleaching associated with specific environmental factors such as temperature, solar radiation, water circulation?	B1 • Ask other reef users to collect similar data.	B2 • Get local weather data from meteorological office on air temperature, sun hours, and wind. • Consult with oceanographers regarding the circulation patterns, water exchange and any upwelling features in the area. • Compare bleaching records with hotspots and degree heating weeks on NOAA's website.	B3 • Install recording temperature loggers at main bleaching sites. • Install remote weather stations to record temperatures, wind and solar radiation. • Measure currents and tidal flow at key sites. • Acquire and analyse remote sensing data to correlate bleaching records with thermal anomalies and degree heating weeks.
C. How long will it last and is it a recurring event?	C1 • Ask local reef users for details on bleaching events and record these on BleachWatch questionnaires.	C2	C3 • Repeat detailed observations in A3. • Repeat same observations for any subsequent bleaching events.
D. What are the ecological impacts on the reef system?	D1 • Conduct before and after bleaching observations including mortality/recovery.	D2 • Measured estimates of benthic cover through time (transects/quadrats).	D3 • Measured estimates of benthic cover through time at higher taxonomic resolution (transects/quadrats). • Transects include other macro-invertebrates. • Fish abundance and diversity surveys.
E. Are adjacent human impacts causing or exacerbating the bleaching?	E1 • Note location, timing (onset, duration, cessation) and severity of local human impacts. • Ask other reef users to give you similar information.	E2 • Collect information on key environmental variables at impact sites (turbidity, sedimentation, gross pollution indicators).	E3 • Detailed surveys at control and impact sites. • Collate existing data on human impacts such as water quality, chronic disturbance from destructive fishing.

2. Early Warning System

Mass coral bleaching is preceded by a series of stages. Beginning with the build-up of climatic conditions that warm sea temperatures, above-average water temperatures follow, which in turn can lead to patchy bleaching or bleaching of more vulnerable coral species. If stressful conditions persist, widespread bleaching of a range of coral species can ensue, resulting in a mass bleaching event. The onset of each of these stages can be used to provide an early warning of a mass bleaching event.

The GBRMPA Early Warning System consists of three elements designed to detect the onset of each of the three stages that lead to a mass coral bleaching event:

1. *Climate Monitoring.* Development of weather conditions that are conducive to elevated sea temperatures.
2. *Sea Temperature Monitoring.* Persistence of increased sea temperatures to levels known to cause stress to corals.
3. *BleachWatch*. Early signs of bleaching on reefs and the spatial extent and severity of any bleaching.

2.1 Climate Monitoring

Above-average sea temperatures are associated with El Niño conditions in many reef regions around the world. While the El Niño Southern Oscillation is an important influence on weather patterns over eastern Australia, other factors are also known to result in high sea temperatures in the GBR region. In particular, delayed or weak development of the monsoonal trough over northern Australia during summer appears to be a strong precursor to the anomalously warm conditions that cause stress to corals. Based on an emerging understanding of the relationship between weather and sea temperatures for the GBR, current and forecast weather conditions can provide a useful indicator of pending warming of waters in the GBR, and thus serve as early warnings of potential stress.

Seasonal climate predictions will be reviewed in the early stages of summer to monitor the development of regional weather patterns that may lead to anomalous sea temperatures. These will be complemented with long- to mid-range weather forecasts as the summer progresses.

Objectives:	Monitor climate and weather conditions in the lead up to summer to assess risk of elevated sea temperatures.
Strategies:	• Monitor long-range climate predictions and weather forecasts. • Obtain 4-Day forecasts and weather summaries from the Bureau of Meteorology. • Explore the value of long-range forecasts for predicting potential warming conditions.
Triggers:	Forecasts of calm, clear conditions, above average summer temperatures, or below average rainfall will trigger logistic preparations for the Bleaching Assessment and Monitoring component.

2.2 Sea Temperature Monitoring

Sea temperatures on the GBR are an indicator of actual stress on corals, and thus serve as an early warning of potential bleaching on the GBR. The NOAA HotSpots programme provides regional-scale near real-time measurements of sea surface temperature (SST) anomalies above the maximum expected summertime temperature. HotSpots and Accumulated Heat Index products from the NOAA web site provide reliable indicators of levels of heat stress in reef regions, and coral bleaching events have been noted in areas where the HotSpots are greater than 1°C anomalous. Over the last year, the GBRMPA has been developing ReefTemp, an improved sea temperature monitoring product for the GBR region with the Bureau of Meteorology (BoM) and the Commonwealth Scientific and Industrial Research Organisation (CSIRO). ReefTemp improves the GBRMPA's ability to monitor thermal stress, and allows for the now-casting of bleaching risk at the scale of an individual reef (~2 km resolution). Images of the (a) SST anomaly (above the long-term average temperature for that month); (b) number of degree heating days and (c) Rate of Heat Stress Accumulation are updated on the ReefTemp website daily.

Excessive and persistent SST anomalies indicate sea temperatures are approaching levels that are known to be stressful to corals, and therefore provide an early warning of coral bleaching. The development of conditions likely to induce bleaching will be monitored using ReefTemp and the accumulated stress indices therein as indicators of local thermal stress during the summer.

In addition, in situ measurements of local sea temperatures are available from a network of weather stations on the GBR. These weather stations record water temperature at the surface and 6 m depth, providing important information about any depth-related variability in water temperatures, while also providing a mechanism to ground-truth ReefTemp predictions.

A network of temperature loggers is also maintained in collaboration with the Australian Institute of Marine Science (AIMS) and the CRC Reef. The lengthy retrieval times required for these loggers preclude them from contributing to an early warning system. However, the data that they provide has proven invaluable in retrospective analyses of the links between sea temperatures and coral bleaching, enabling AIMS scientists to develop bleaching thresholds for key locations throughout the Great Barrier Reef.

Objectives:	Obtain early warnings of temperature stress and conditions that could lead to bleaching on the GBR over summer.
Strategies:	• Actively monitor ReefTemp. • Evaluate sea temperature from weather station data to validate the remotely sensed sea temperatures used in ReefTemp. • Actively monitor NOAA HotSpots.
Triggers:	The onset of stressful conditions will trigger increased vigilant monitoring of coral condition through BleachWatch and site inspections (Table 2). Stressful conditions (event triggers) are defined in Table 4.

2.3 BleachWatch

The initial onset of mass coral bleaching can range from gradual and patchy to rapid and uniform, and can occur with varying synchrony over hundreds or thousands of square kilometres. Detecting the early signs of a mass bleaching event requires a wide network of observers providing regular reports of conditions throughout the region. BleachWatch is a community monitoring initiative that has been designed to provide reliable reports of reef condition from a wide range of reef sites throughout the GBR. BleachWatch is built on a network of regular reef users, including tourism professionals, scientists, conservation groups, fishers and community members who voluntarily monitor and report on conditions at reefs that they visit regularly.

BleachWatch was initially established at the start of 2002, during the major bleaching event that occurred that summer on the GBR. Participants visiting reefs between Port Douglas in the north and Bundaberg in the south have been enlisted to provide regular reports on the appearance and health of the sites they visit during summer. The number of participants and geographic coverage of BleachWatch has continued to grow, with currently more than 100 participants.

BleachWatch participants are provided with a BleachWatch kit and asked to complete purpose-designed monitoring forms on a weekly basis. Participants are asked to provide general observer information, as well as details about their site, type of habitat and specific weather conditions that are known to influence risk of bleaching (such as water temperature, cloud cover, air temperature, and wind speed). Detailed information about reef condition and bleaching observations is also collected (a copy of the form is given in Appendix A). Once the observer has submitted the first site report to the GBRMPA, they need only fill out sections 1 and 2 and tick 'no change' unless coral bleaching is observed or there has been a change in conditions at the reef site. It is estimated that completion of the form takes approximately 10 minutes per week for each participant. The data submitted by BleachWatch observers will be compiled and synthesised into summary reports during the summer season; these will be sent to participants for their information and for display to their clientele on board tourism vessels. The data collected is reviewed weekly to identify where coral bleaching has been sighted, whether it is spatially or locally significant and whether the Assessment and Monitoring component of the Response Plan should be implemented.

Less regular or one-off reef visitors can also submit observations on reef status and coral bleaching to a central database on the GBRMPA website. Reports will be compiled onto maps every 1-2 months during the summer season, and published on the website.

Objectives:	To detect the early stages of coral bleaching events over a wide geographic area. To involve the community in reef monitoring, reef education and reef conservation relating to coral bleaching and climate change.
Strategies:	• Develop and maintain a network of regular reef users who will provide reports of coral bleaching conditions at reefs that they regularly visit. • Provide operators with a BleachWatch kit that assists them in reporting on reef conditions and detecting coral bleaching. The BleachWatch kit includes: - Interpretive material on coral bleaching and climate change - Examples of coral growth forms - Examples of bleaching severity - Monitoring forms - Instructions for the monitoring form - In-water identification wrist band • Regularly enter and evaluate data received to determine the composition of each reef to assist with evaluations of bleaching susceptibility. • Provide regular feedback in the form of summary site reports to all participants. • Develop and maintain a website providing information on BleachWatch, including a downloadable version of the datasheet, on-line reporting form and copies of the site reports for each participant. • Provide regular feedback in the form of reports, web updates and informal communications to all participants.
Triggers:	Reports of spatially extensive or severe local bleaching will trigger the Bleaching Assessment and Monitoring component.

2.4 BleachWatch (Aerial)

BleachWatch (Aerial) is the product of broad-scale aerial surveys conducted in previous years. BleachWatch (Aerial) is a partnership between the GBRMPA and Coastwatch and benefits from the active involvement of Coastwatch pilots and crew who visit an extensive number of reef sites regularly throughout summer. Pilots and crew are trained in identifying possible bleaching from the air and asked to take geo-referenced photographs for later analysis. The information collected by BleachWatch (Aerial) helps GBRMPA detect the onset of bleaching and helps assess the full spatial extent and distribution of a bleaching event.

Objectives:	Assess the spatial extent and distribution of coral bleaching for the entire GBR.
Strategies:	• Implement a partnership with Coastwatch to incorporate bleaching observations and photography into routine surveillance flights covering reefs spanning the full length and breadth of the GBR.
Triggers:	Confirmation of conditions conducive to bleaching from the climate and sea temperature monitoring will trigger the broad-scale synoptic surveys.

3. Bleaching Assessment and Monitoring Component

The objective of the Bleaching Assessment and Monitoring component is to assess the spatial extent and severity of coral bleaching events and determine the ecological implications (for example coral mortality and shifts in community structure) resulting from coral bleaching.

Timing is critical for the implementation of bleaching surveys. A bleaching event can progress quite quickly once visible signs of stress are prevalent, with only four to six weeks required for bleached corals to either recover or die. On the Great Barrier Reef, the peak of previous bleaching events has occurred around March-April. If assessments are delayed beyond this time, they are likely to provide an underestimate of the amount of bleaching that has occurred as many corals may have died or recovered, making it difficult to confidently attribute any coral mortality to bleaching-related stress.

A tiered approach using two methods will be used to provide the best possible combination of spatial coverage and detailed information. The Bleaching Assessment and Monitoring component is comprised of broad-scale synoptic surveys and in-water bleaching surveys. The broad-scale synoptic surveys will use both MERIS and Quickbird satellite imagery to access different spatial resolution data. CSIRO will provide the MERIS mapping and the Centre for Remote Sensing and Spatial Information Science at the University of Queensland will provide the Quickbird high resolution and field mapping. The bleaching surveys will collect detailed ecological information from a set of established reef sites that represent cross-shelf as well as latitudinal reefs. This tiered approach is the most effective for obtaining a synoptic overview of where bleaching is occurring from a GBR-wide perspective.

3.1 Broad-scale Synoptic Surveys

The correlation between sea surface temperatures and bleaching risk is an area of active research, and early results are indicating that sea surface temperatures are reliable indicators of regional-scale stress, but not an accurate predictor of bleaching at individual reefs. Broad-scale synoptic surveys are the most effective method for obtaining an overview of the extent of bleaching over spatial scales that are relevant to management on the GBR (ie hundreds to thousands of kilometres). As well as being important for temporal comparisons of the extent of future bleaching events, broad-scale synoptic surveys help to identify the reefs or regions worst affected by thermal stress.

During the 2005/2006 summer, a pilot project trialed MERIS remote sensing mapping to detect coral bleaching at 300 m resolution. The pilot project included field validation of MERIS and Quickbird satellite images to provide a high level of detail on the health of corals during a localised bleaching event. Due to the high level of resolution, the pilot project was limited in spatial coverage to only inshore reefs around the Keppel Islands. The MERIS data was also captured for other reefs in the GBR where bleaching did not occur, to test the mapping algorithm developed at CSIRO, for both inshore and offshore reefs.

As there was a localised bleaching event, Quickbird (2.4 m pixels) image data was captured over the Keppel Island sites where bleaching surveys were conducted. These images covered 10 km x 10 km sections and were used to map bleached versus non-bleached coral areas.

Objectives:	Assess the spatial extent and distribution of coral bleaching for select locations along the GBR.
Strategies:	• Utilise satellite imagery (at a spatially relevant scale) to document coral cover and extent of bleaching at target reefs. • Build a hierarchical system using satellite imagery, and in-water data to get a complete picture, and possibly predictive capacity for the extent of bleaching.

3.2 Bleaching Surveys

Although the phenomenon of bleaching has received much attention, the ecological significance of mass bleaching is still poorly understood. Severe bleaching events have the potential to kill large areas of living coral, and consequently cause major disturbance to coral reef ecosystems. However, the fate of bleached corals cannot readily be predicted from observations of the severity or extent of bleaching. Widespread bleaching does not necessarily equate to widespread coral mortality. To better understand the long-term implications of these events, information on the extent and patterns of coral mortality that result from bleaching need to be measured.

In-water bleaching surveys will provide more precise information about the percentage and types of corals that bleach, and then subsequently die or survive. Over longer time frames, the bleaching surveys will also enable the direction and rate of community recovery to be evaluated. The quantitative data provided by the bleaching surveys will enable the testing of hypotheses about differences or trends between sites or through time. Differences in coral community structure that may occur because of bleaching and mortality will be detected, and information on whether certain community types are more susceptible to bleaching than others can be obtained.

Bleaching surveys will use a combination of rapid visual assessment and more detailed video transects to provide information about the bleaching event and its ecological impacts. The rapid assessment and video transects will be done simultaneously at all sites. The two techniques are designed to be complimentary: the rapid assessment provides basic information about the severity of the bleaching event in near real-time, while the video transects provide more detailed information, but require intensive analysis that normally takes weeks to months to complete. Details on site selection, integration with the AIMS LTMP and survey methods are outlined in the following section..

Objectives:	Assess the percentage of coral bleaching, affected species and mortality for select reefs along the GBR.
Strategies:	• Rapid visual assessments to document coral cover, community composition, and severity of bleaching at target reefs. • Video transects to quantify coral cover, community composition, and extent and pattern of bleaching at target reefs. • Ground truth aerial data using in-water fine scale surveys.

3.2.1 Spatial and Temporal Scale of surveys

The Coral Bleaching Response Plan will build on existing programmes, in particular the AIMS Long Term Monitoring Programme (LTMP), which has a suite of core sites that are surveyed annually for benthic cover and diversity, fish diversity and abundance and other stressors (eg COTS). By surveying the AIMS LTMP sites during a bleaching event, important baseline and recovery data can be incorporated in any assessments. Additionally, the AIMS targeted bleaching surveys will complement the GBRMPA surveys.

The dynamic nature of coral bleaching requires multiple temporal and spatial surveys in order to characterise the extent and severity of bleaching that occurs, and the ecological implications (ie the amount of mortality that occurs). This ideally requires three temporal surveys:

Baseline. The first survey is used to document reef status (coral cover and composition) prior to any changes caused by bleaching. This is best conducted before the onset of bleaching. The Response Plan will utilise the AIMS LTMP data from the previous survey period.

Event monitoring. The second survey will be timed to coincide with the peak of the bleaching event, and is used to document the spatial and taxonomic patterns of bleaching. This information is necessary to report on the extent and severity of bleaching, and to interpret the causes and significance of changes in reef condition.

Recovery. The third survey should be done shortly after the bleaching event, but not until all corals have either recovered or died. This survey determines the ecological impacts of the bleaching by assessing changes in coral cover or composition attributable to the bleaching event. The AIMS LTMP data set from the next survey period will be used to determine reef status after the bleaching event.

Structured survey sites will be monitored from Lizard Island in the north to One Tree Island in the south and have been selected to match the AIMS Long Term Monitoring Programme (LTMP) sites (see Section 3.2.2).

Table 2. Location of sites for fine scale ecological impact assessments
(I), inner-shelf reef; (M), mid-shelf reef; (O), outer shelf reef.

Transect Region	Reef Name
Far Northern (Cooktown to Lizard I.)	Martin Reef (I) Linnet Reef (I) Decapolis Reef (I) MacGillivray Reef (M) Nth Direction I. (M) Lizard I. lagoon (M) Yonge Reef (O) Carter Reef (O) No Name Reef (O)
Northern (Cairns)	Green I. (I) Low Isles (I) Fitzroy I. (I) Mackay Reef (M) Michaelmas Cay (M) Hastings Reef (M) St Crispin Reef (O) Opal Reef (O) Agincourt No.1 Reef (O)
Central (Townsville)	Pandora Reef (I) Havannah I. (I) Middle Reef (I) Davies Reef (M) Rib Reef (M) John Brewer Reef (M) Chicken Reef (O) Dip Reef (O) Myrmidon Reef (O)
Southern (Whitsundays)	Hayman I. (I) Border I. (I) Langford and Bird I. (I) Reef 19131S (M) Reef 19138S (M) Reef 20104S (M) Slate Reef (O) Hyde Reef (O) Rebe Reef (O)
Far Southern (Capricorn Bunkers and Swains South)	Nth Keppel I. (I) Pelican I. (I) Humpy I. (I) Gannet Cay (M) Chinaman Reef (M) Reef 21529S (M) Turner Cay (O) Wreck I. (O) One Tree I. (O)

3.2.2 Survey Sites

Each survey will assess the condition and composition of the benthic community along five cross-shelf transects (Table 2) lists the reef sites for each of these transects). These will be located at latitudes centred on Lizard Island, Cairns, Townsville, Whitsunday Islands and the Capricorn Bunker Group.

Forty five sites have been selected based on existing AIMS LTMP site locations, to provide for a long-term data set on coral cover and community composition at the sites. Three inshore, three mid-shelf and three outer shelf reefs have been selected for each transect. Sites were selected from the AIMS LTMP database based on the existence of previous coral bleaching survey data (1998 and 2002), accessibility under predominant weather conditions and location of Reef Water Quality Protection Plan survey sites.

The benefit of this approach is that baseline and recovery data for the deep transects can be obtained from the AIMS LTMP routine surveys and thus reduce the need for multiple GBRMPA survey trips and duplication with existing programmes. However, the LTMP only surveys the coral community on the lower reef slope (6-9 m) while the GBRMPA Response Plan also surveys the community on the upper slope (3-4 m), as this is the area most affected by coral bleaching. It is necessary to obtain a quantitative baseline assessment of the upper slope community at all of the survey sites to enable us to evaluate the long-term ecological impacts of coral bleaching on the Great Barrier Reef.

Some remote locations along the GBR have been omitted from the standard sites selected, such as the northern Swains and Pompey Complex. These locations are rarely visited and do not have long-term datasets as they are not AIMS LTMP survey sites. If a significant bleaching event occurs, these sites will be surveyed if logistics allow.

Additional sites may be surveyed using manta tow or rapid assessment techniques in a bleaching event. These sites would be selected to match those surveyed in the 1998 and 2002 bleaching events, reefs surveyed under the Reef Plan monitoring programme (for example Daydream I., Dent I. and Double Cone I.), and other sites of interest. They will be surveyed as time and resources permit

3.2.3 Survey Design

Three shelf positions will be surveyed in each transect: inshore, mid-shelf and outer shelf. Three replicate reefs will be surveyed at each shelf position. Sites will be those established by the AIMS LTMP and will be divided into two depth zones: shallow and deep. The shallow station includes the reef crest and upper slope from about 1- 4 m in depth. The deep station includes the mid to lower reef slope from 5-10 m. Actual depths at each station vary according to the reef morphology and coral community type and distribution. At more turbid stations, or areas with poorer reef development, these depths may be shallower, while at stations that are generally characterised by clear conditions they are deeper. In the few stations with very restricted reef development, only the shallow depth zone is present. These depth zones, once established, will be fixed for each station.

Three random transects will be surveyed at each depth at each station. Random transects will be used rather than fixed transects to reduce the time required for establishment and survey, avoid unsightly markers on the reef and ensure independence among consecutive surveys. Each transect will be surveyed simultaneously by two independent methods: a rapid visual assessment and video transects.

Two divers will swim along a 50 m belt transect, one recording information on the Rapid Assessment Survey data sheet and the other recording the same substratum area with an underwater video camera. The rapid assessment survey will record observations on the condition of corals and other benthos within a band 5 m wide along the length of the transect. Three sets of information will be recorded: station information; general coral and bleaching observations; and detailed information for selected coral groups. All data will be entered directly onto the specially designed Rapid Assessment Survey data sheets. The categories for estimating per cent cover and progress of bleaching have been standardised on the survey sheet to enable consistent surveying methods by different observers. A table showing schematic representations of per cent cover will be utilised to maximise consistency in estimates made underwater.

Video transects will be recorded at a distance of 40 cm above the substrate at a speed of 10 metres per minute (in accordance with the standard protocol used by AIMS).

3.2.4 Data Analysis and Management

Video transect data will be analysed by an appropriately skilled and experienced analyst, and stored in a database maintained by GBRMPA and shared with AIMS. Data from video transects will be used to quantify coral cover, community composition, and extent and pattern of bleaching at target reefs. Data collected using the Rapid Visual Assessment surveys will be stored in a database maintained by GBRMPA. Data will be used to document coral cover, community composition, and severity of bleaching at target reefs.

3.2.5 Complementary Studies

AIMS Climate Change Programme: temperature loggers

AIMS coordinate the Sea Temperature Monitoring Programme, which includes the deployment and collection of in situ data loggers, and the maintenance of a network of weather stations. Data loggers have been placed on the reef flat, at or near Lowest Astronomical Tide, and on the reef slope at ~50 locations spanning the extent of the GBR. At some locations, loggers have been placed on the upper reef slope (~5-9 m), or on the deep reef slope (~20 m). Following the 1998 and 2002 bleaching events, data from these loggers allowed for a better understanding of the link between temperature and the severity of bleaching responses. Bleaching 'thresholds' developed from this research can currently be monitored at the weather station sites on the Reef Futures website, and are an important component of the Early Warning System in the Response Plan. Additionally, AIMS targeted bleaching surveys will complement the GBRMPA surveys.

AIMS LTMP
The AIMS Long-term Monitoring Programme has been tracking the condition of the Great Barrier Reef for more than a decade, by surveying fish, corals, crown-of-thorns starfish, and coral disease. The AIMS monitoring team is the one of the premier bodies focussing on the condition of coral reef ecosystems in the Great Barrier Reef World Heritage Area. The GBR Response Plan utilises the information collected under the LTMP to obtain baseline and recovery data.

Reef Water Quality Protection Plan
In addition to the fine-scale ecological surveys, water quality data collected for the Reef Water Quality Protection Plan (Reef Plan) marine monitoring will be utilised to assess the influence of water quality stressors on susceptibility to bleaching and recovery post-bleaching. The Reef Plan monitoring programme will collect information on temperature, salinity, turbidity, chlorophyll a, sediment and nutrients loads, flood events (pollutant loads, salinity and flow), pesticide concentrations and reef health at a number of inshore locations. Many of these sites overlap with proposed fine scale ecological impact assessment sites of the GBR Response Plan and there is the opportunity to correlate these sites further for broad-scale synoptic surveys and bleaching surveys during a bleaching event.

4. Communication Strategy

Coral bleaching and global climate change are issues that attract strong interest from the public, the media and senior decision-makers. It is important to proactively release accurate information about coral bleaching events to all stakeholders as it becomes available in order to raise awareness and ensure discussions and debate are well informed. The GBR Coral Bleaching Response Plan will be the main source of timely and credible information on coral bleaching on the GBR, and on the ecological implications for the reef ecosystem.

Information will be delivered directly to stakeholder groups via public meetings, existing formal and informal networks (including GBRMPA initiatives such as Eye on the Reef, Tourism and Recreation Newsletter and LMACs) and email. Information will also be distributed more widely through the GBRMPA website and via media outlets. The Communication Strategy aims to increase awareness of the implications of climate change for the GBR, and the occurrence and consequences of coral bleaching events through a variety of strategies. Information about coral bleaching will be communicated using the following methods:

- In the months prior to the period of high bleaching risk, beginning in November, the website will be reviewed to present the most current information on predicted climate and local weather conditions and the estimated potential for coral bleaching.
- Information about bleaching issues and notification of web updates will be circulated via industry newsletters, meetings, and email lists.

- During summer (December to April), the GBRMPA will post regular web reports (every 2-4 weeks) on bleaching conditions on the GBR.
- Reports will also be sent directly to stakeholder groups (tourism operators, Marine Parks staff, scientists, etc.) via email on a semi-regular basis (every 2-4 weeks).
- Media statements will be prepared and released if/when:
    - conditions develop that indicate a high risk of coral bleaching;
    - a bleaching event occurs (describing spatial extent and general severity); and
    - the bleaching event has concluded (describing coral mortality and ecological impacts).

5. Implementation

The sequence of events and decision points for implementation of the GBR Coral Bleaching Response Plan are shown in the Schedule below (Figure 2). Climate and weather conditions will be monitored from mid-November, approximately three months prior to the period of greatest bleaching risk. Sea temperature monitoring and BleachWatch will be implemented from December each summer. If the onset of high bleaching risk conditions are confirmed, or if there are any reports of significant coral bleaching, the Bleaching Assessment and Monitoring component will be implemented (Figure 2).

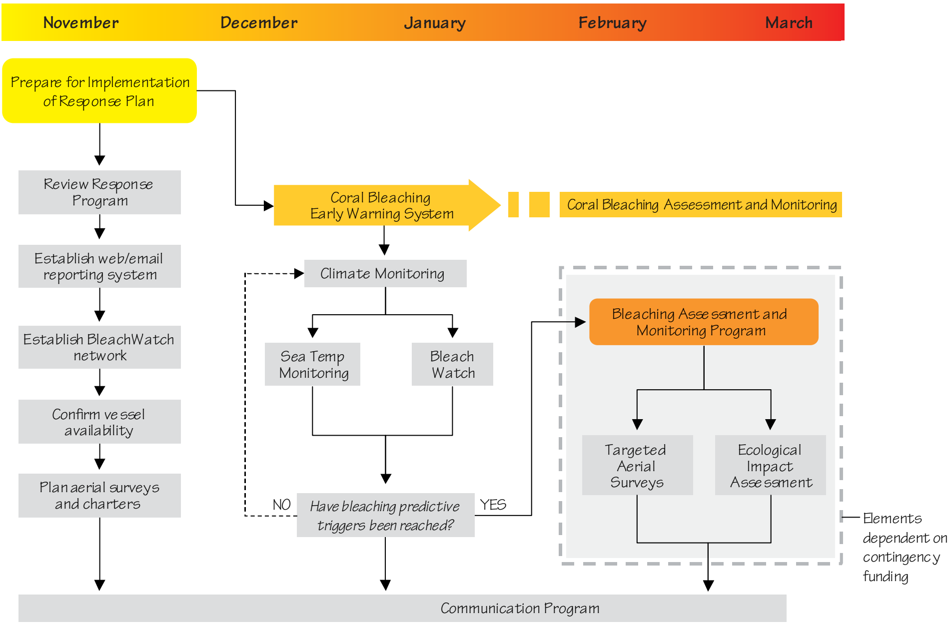


Figure 2 Schedule for the GBR Coral Bleaching Response Plan

5.1 Response Schedule

The GBR Coral Bleaching Response Plan consists of a combination of routine tasks and responsive tasks that are triggered by thresholds.

Routine tasks are designed to provide basic information to help determine if and when a bleaching event is occurring, and to ensure the Climate Change Response Team is prepared for the responsive tasks. Responsive tasks are implemented if it appears that a major bleaching event is imminent, and are designed to provide a more detailed picture of bleaching conditions and their ecological significance. An outline of these tasks is provided below, with a detailed breakdown of tasks provided in Table 3.

5.1.1 Routine Tasks

- Prepare for implementation of responsive tasks.
- Initial assessment of probability of stressful conditions to corals based on long term climate predictions for summer (ie ENSO conditions; development of monsoonal trough).
- Establish bleaching reporting system, including email updates and website.
- Establish BleachWatch networks.
- Monitor weather conditions and sea temperatures and compare against thresholds.
- Update assessment of conditions and predicted levels of stress to corals.
- Solicit and coordinate information about early signs of bleaching through BleachWatch.
- Advise Senior Management and Minister of any increase in bleaching risk or bleaching reports.

5.1.2 Responsive Tasks

- Confirm bleaching reports (site inspections).
- Advise Senior Management, Minister, stakeholder groups and the community of onset of coral bleaching.
- Implement broad-scale synoptic surveys to assess bleaching extent.
- Deploy bleaching survey team to measure extent and severity of bleaching.
- Monitor ecological impacts of bleaching.

Table 3. Coral Bleaching Response Plan: Task Schedule

Trigger type	Timing	Information
Routine: weekly	Monday	Check GBRMPA ReefTemp and NOAA HotSpot maps on web. Receive updated GBR sea temperature graphs from AIMS (operational). Receive high resolution sea temperature maps for GBR (2 km resolution) from BoM. Obtain weather summary for week, eg air temperatures, cloud cover and wind (BoM). Review bleaching reports received via BleachWatch and update maps. Review bleaching reports and images received via BleachWatch (Aerial) surveys and update maps. Print out ReefTemp and NOAA HotSpot maps for STIG Director to brief SMT.
Routine: weekly/fortnightly	Tuesday	Summarise weather, sea and coral conditions and draft updated Bleaching Risk Current Conditions Report for website. Include any recent images that may be available.
Routine: weekly/fortnightly	Wednesday	Have updated Current Conditions Report reviewed, approved and published on external web. Send brief update to all-staff and other lists (ACRS, DDM, AIMS, CRC Reef, Coral-List and BleachWatch participants).
Routine: weekly/fortnightly	Constant	Monitor extent of bleaching using existing information channels and evaluate for trends (ie is the bleaching situation worsening/improving). Advise Senior Management and Minister if dramatic worsening of conditions is evident.
Event-based	Substantial increase in environmental stress[1]	Actively seek and solicit confirmatory bleaching reports from reliable sources, including BleachWatch participants, DDM Field officers, AIMS, other researchers, etc. Alert relevant project coordinators and managers. Brief Senior Management.
Event-based	Moderate bleaching event detected1	Brief Executive and Minister. Prepare media position, draft statement and consult with Media Coordinator and Executive. Brief all staff and stakeholders. Brief collaborators (especially AIMS, NOAA, DDM). Release media statement. Actively promote and solicit submissions to online bleaching reports to provide wide spatial coverage. Implement Bleaching Assessment and Monitoring component.

[1] see Section 5.2 for description of thresholds for event-based tasks.

5.2 Definition of Event Triggers for Implementation Plan

The triggers for monitoring tasks and briefings outlined in the Implementation Plan (Table 5) are defined in Table 4 below.

Table 4. Definition of event triggers for Implementation Plan

Trigger	Definition
High bleaching risk	• Persistence of strong hotspots (anomaly > 1.5 °C) for 2 weeks or very strong hotspots (anomaly > 2 °C) for 1 week over majority of GBR region; • degree heating days index is greater than 21 at multiple sites; • bleaching thresholds exceeded at inshore and offshore sites; **or** • there are anecdotal reports of bleaching from multiple sites.
Low bleaching level	• Reliable reports of low coral bleaching (1–10 % of colonies completely white) from multiple sites from multiple locations spanning at least two GBRMP sectors; **or** • reliable reports of mild bleaching (10–50%) from a few sites only, scattered throughout the GBRMP or concentrated in only one sector.
Moderate bleaching level	• Reliable reports of moderate coral bleaching (10–50% of colonies completely white) from multiple sites from multiple locations spanning at least two GBRMP sectors; **or** • reliable reports of severe bleaching (>50%) from a few sites only, scattered throughout the GBRMP or concentrated in only one sector.
Severe bleaching level	• Reliable reports of severe to extreme coral bleaching (>50% of colonies completely white) from multiple sites spanning multiple GBR sectors.

Table 5. Implementation Plan for Summer Period 2005-2006

TRIGGER[1]	ACTIONS						
	Monitoring			Briefings			
	Site inspections	Broad scale synoptic	Bleaching surveys	Brief Senior Management	Brief Minister	Press release	Message
1 December				✓	✓	✓	Summer approaching; bleaching risk period; GBRMPA is prepared
20 December				✓			Temperature trends for December; plans for Christmas break
High bleaching risk	✓			✓	✓		Temperatures unusually high; coral bleaching event probable
Moderate bleaching	✓	✓	✓	✓	✓	✓	High temperatures recorded; moderate bleaching observed; areas worst affected
Severe bleaching[2]	✓	✓	✓	✓	✓	✓	Very high temperatures recorded; severe bleaching observed; areas worst affected; mortality likely
15 February[3]				✓			Temperature trends for first half of summer; summary of reports of coral bleaching
31 March (if no significant bleaching observed)				✓	✓	✓	Summer concluding; bleaching risk period over; no significant bleaching observed
31 March (if moderate or severe bleaching reported)				✓	✓	✓	High water temperatures recorded during summer; bleaching observed; preliminary assessment of extent and severity; detailed surveys underway
31 April (if moderate or severe bleaching reported)				✓	✓	✓	Summary of full extent and severity of bleaching; implications for GBRMP
Monthly[4]				✓			Updates on temperature trends and coral condition; also publish to web and email to all staff etc.

[1] Event-based triggers are defined in Table 3 of the GBR Coral Bleaching Response Plan

[2] Aerial surveys, site inspections and bleaching surveys are likely to already have been triggered by moderate bleaching levels

[3] This briefing will not be necessary if a moderate or severe bleaching event has already been declared

[4] These update reports may be made twice-monthly if conditions are changing rapidly

6. References

English S, Wilkinson C and Baker V (1997). *Survey Manual for Tropical Marine Resources*. 2nd edition., ASEAN, Australia Marine Science Project, Living Coastal Resources, Australian Institute of Marine Science, Townsville, Australia.

Wilkinson C (2004). *Status of Coral Reefs of the World: 2004 Summary*. Australian Institute of Marine Science, Townsville, Australia.

Appendix A. BleachWatch reporting form

Australian Government
Great Barrier Reef
Marine Park Authority

BleachWatch
observe to conserve

1. Observer Details

Observer ID:.. Observation Date:..

Last Name: .... First Name: .... Email:................................

Phone: .... Vessel/Organisation: ....

Observer Category: Reef Visitor ☐ Marine Tourism Industry ☐ Scientist ☐

Other*(Please specify)*: ....

2. Information about the site

Reef ID /Name: .... Site name: ....

Habitat: Lagoon ☐ Crest ☐ Slope ☐ Flat ☐ Bommie field ☐ Front Reef ☐ Back Reef ☐

Other: ....

Cloud Cover *(please circle)*: Clear Partly Cloudy Mainly cloudy Overcast

Air Temp: ☐ Water Temperature: 0-3m ☐ 5-10m ☐

Wind Speed *(please circle)*: 0 0-5kn 5-10kn 10-15kn >15kn

Is this your first submission? No Yes Has this site changed since your last submission? Yes ☐ No change ☐

3. Reef Condition

- Live Coral at this site *(Table 1)*:

Category 0 (0%)	☐	Category 3 (31-50%)	☐
Category 1 (1-10%)	☐	Category 4 (51-75%)	☐
Category 2 (11-30%)	☐	Category 5 (76-100%)	☐

- Three Most Common Coral Types Present:
(in order of abundance)

Branching	☐	Bushy	☐
Plate	☐	Digitate	☐
Massive	☐	Encrusting	☐
Soft Coral	☐		

4. Bleaching Observations

- Bleached Coral at this site *(Table 1)*:

Category 0 (0%)	☐	Category 3 (31-50%)	☐
Category 1 (1-10%)	☐	Category 4 (51-75%)	☐
Category 2 (11-30%)	☐	Category 5 (76-100%)	☐

- Types Bleached *(Table 2)*:

Branching	☐	Bushy	☐
Plate	☐	Digitate	☐
Massive	☐	Encrusting	☐
Soft Coral	☐		

- Most Common Level of Bleaching Severity *(only select one)*:

Bleached only on upper surface ☐
Pale/Fluoro (very light or yellowish) ☐
Totally bleached white ☐
Dead coral with algae ☐

Indicate the depth range of the **bleaching**

Min: ☐ Max: ☐

5. Detailed Types Present / Bleached

	Present	Bleached		Present	Bleached		Present	Bleached
Acropora	☐	☐	Turbinaria	☐	☐	Porites	☐	☐
Fungiidae	☐	☐	Stylophora	☐	☐	Sarcophyton	☐	☐
Pocillopora	☐	☐	Faviidae	☐	☐	Lobophytum	☐	☐
Seriatopora	☐	☐	Montipora	☐	☐	Sinularia	☐	☐

Comments: ....

....

Appendix B. Rapid Assessment Survey data sheet

GBRMPA Rapid Assessment Monitoring Sheet

Region:
Reef Name:
Date:
Time:
Observer:
Dive Buddy:
Vessel:
Site Details:
Water Temp:
Surface:
Depth:
Notes:

Benthos	% cvr (1)	Transect 1					% cvr (1)	Transect 2					% cvr (1)	Transect 3				
Abiotic	▨	**Notes**					▨	**Notes**					▨	**Notes**				
Sand																		
Rubble																		
Other																		
Other Live	▨						▨						▨					
Coral		**Bleaching severity (2)**						**Bleaching severity (2)**						**Bleaching severity (2)**				
		0	1	2	3	4		0	1	2	3	4		0	1	2	3	4
Soft	▨						▨						▨					
Hard	▨						▨						▨					
Acropora																		
Montipora																		
Pocilloporids																		
Porites																		
Faviids																		
Algae	▨	**Notes**					▨	**Notes**					▨	**Notes**				
Fleshy/upright/macro																		
CCA																		
Filamentous (Turf)																		
Ephemeral/scuzzy																		
Total	100%						100%						100%					
Canopy height min/max/mode (cm)																		
Other Impacts																		

Reef flat observations

Other notes and observations

Appendix C. Code tables for key variables

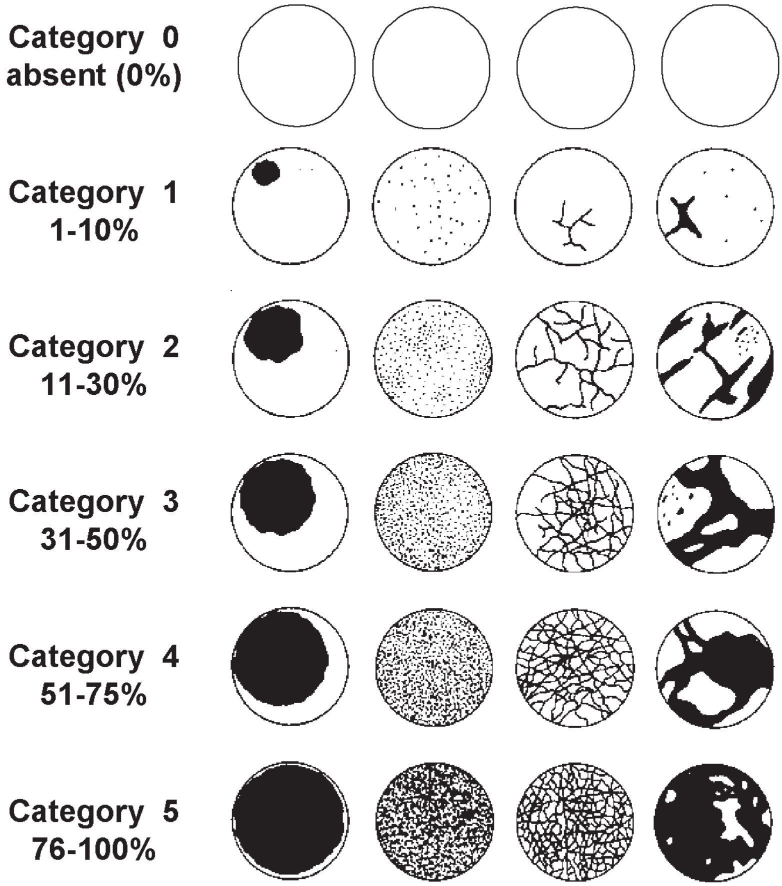
Site bleaching category table

Index	%	Description	Visual Assessment
0	<1	No bleaching	No bleaching observed, or only very occasional, scattered bleached colonies (one or two per dive)
1	1-10	Low level bleaching	Bleached colonies seen occasionally and are conspicuous, but vast majority of colonies not bleached
2	10-50	Moderate level bleaching	Bleached colonies frequent but less than half of all colonies
3	50-90	Severe bleaching	Bleaching very frequent and conspicuous, most corals bleached
4	>90	Extreme bleaching	Bleaching dominates the landscape, unbleached colonies not common. The whole reef looks white

Colony bleaching table (for use in Line Intercept or Video Transect surveys)

Category	Description
0	No bleaching evident
1	Partially bleached (surface/tips); or pale but not white
2	White
3	Bleached + partly dead
4	Recently dead

Appendix D. Schematic representations of per cent cover



(Adapted from English et al 1997; after Dahl 1981. Category 0 added.)

NOTES

NOTES

BIOGRAPHIES

Dr Paul Marshall leads the Climate Change Response Program for the Great Barrier Reef Marine Park Authority. His work with a range of scientific, government and non-government organisations has focussed on improving knowledge about the implications of climate change for coral reef ecosystems. He plays a key role in national and international initiatives to adapt coral reef management in the face of climate change. He has published numerous scientific papers, book contributions and reports on coral bleaching and climate change impacts on tropical marine ecosystems.

Heidi Schuttenberg specialises in coral reef management and policy, focussing on Southeast Asia and the U.S. She previously worked for NOAA leading a series of initiatives to strengthen management for key threats to U.S. reefs, with special emphasis on options for responding to climate change and mass coral bleaching. She is active in international policy forums related to reef management and has worked on both local and regional projects to support coral reef management in Southeast Asia. She was awarded a Fulbright scholarship to Thailand and is currently completing her PhD at James Cook University in Australia.

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