MANAGING FOR MASS CORAL BLEACHING

CHAPTER I

1. MANAGING FOR MASS CORAL BLEACHING

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].

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

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.

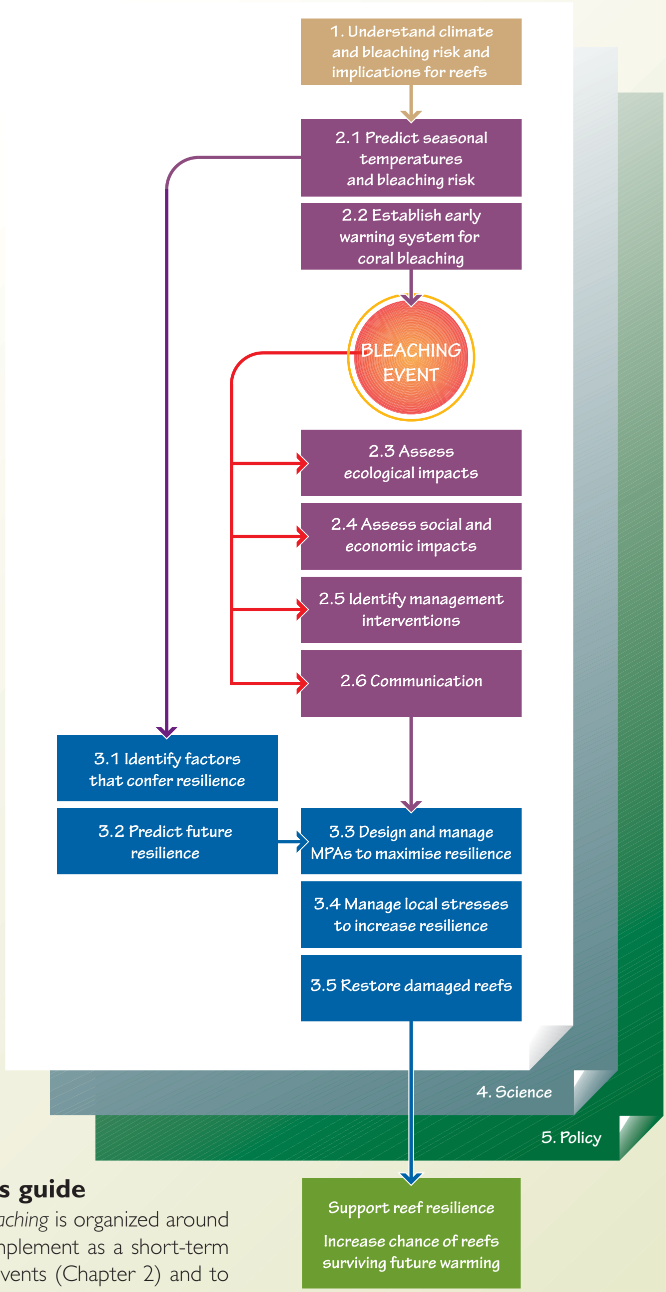

Figure 1.1 How to use this guide

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.

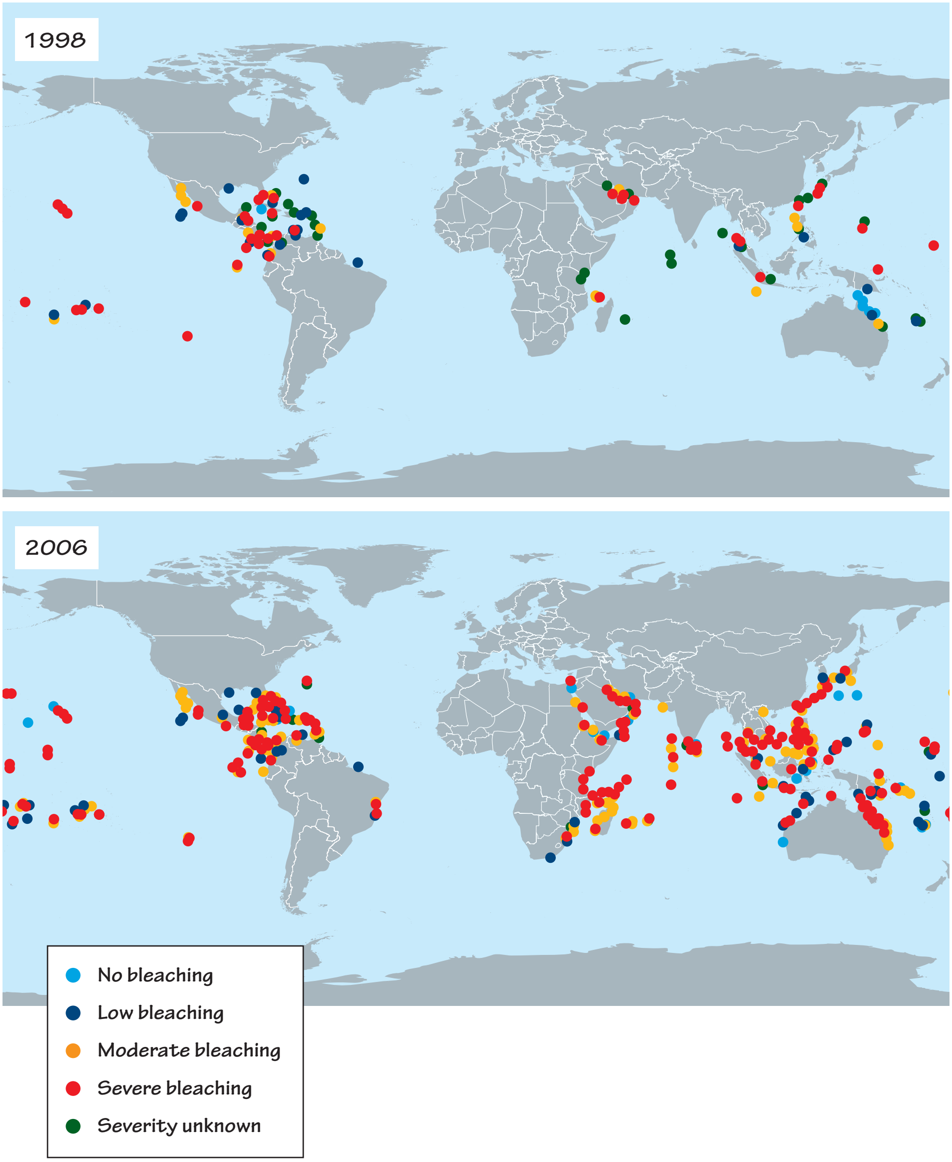

Figure 1.2 Global trends in the extent and severity of mass bleaching

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

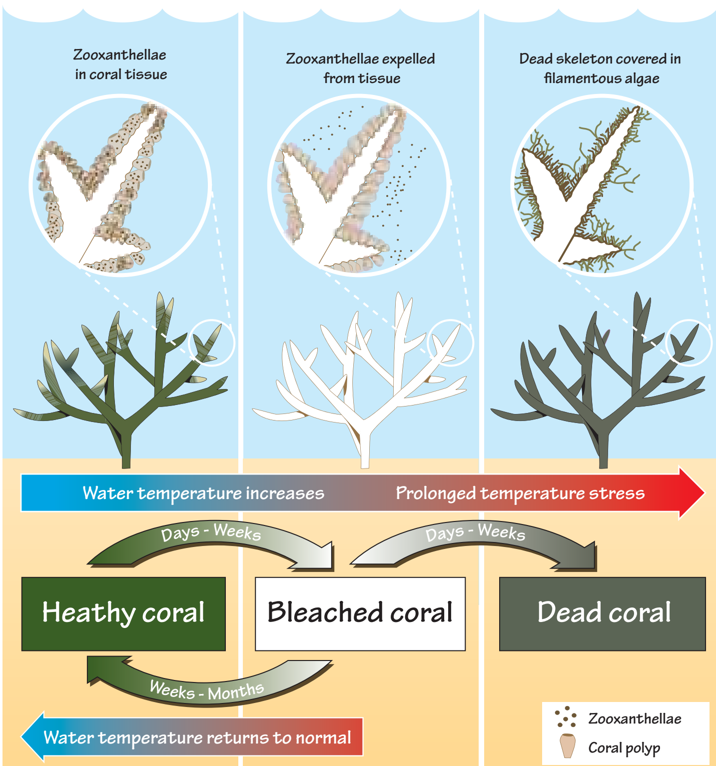


Figure 1.3 Stages in mass coral bleaching

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.

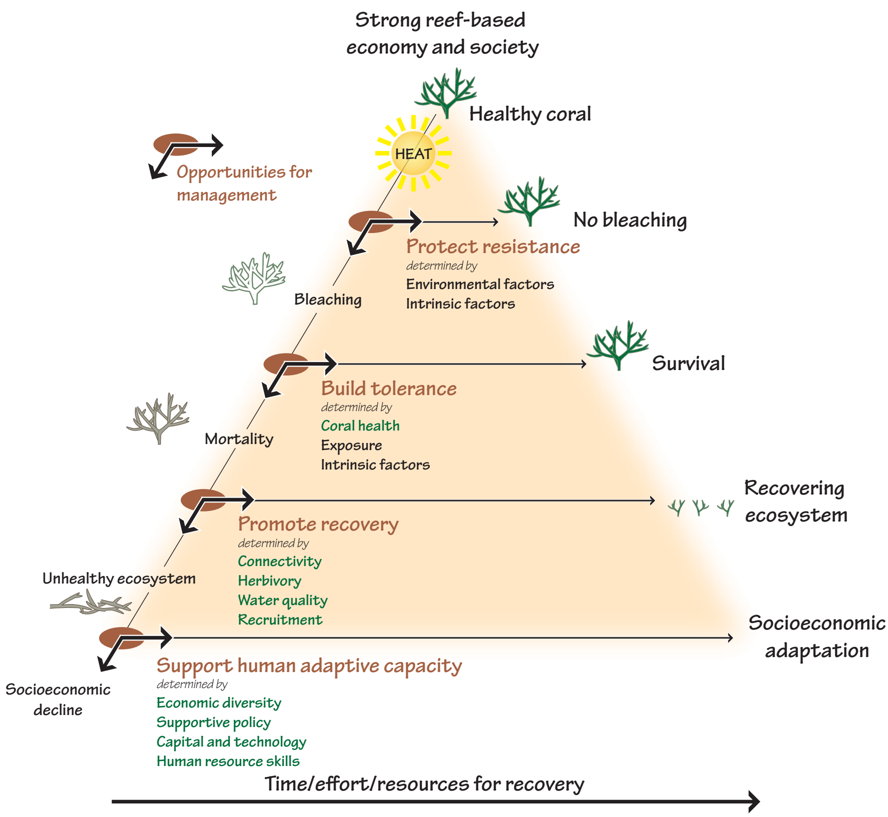


Figure 1.4 Opportunities for management intervention

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).

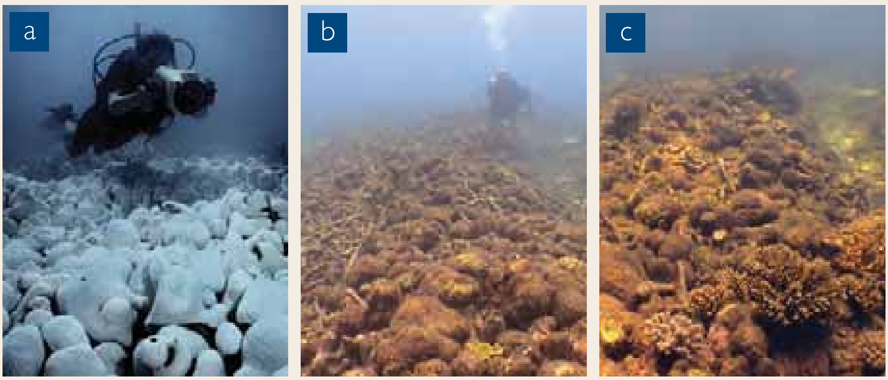
Reducing or eliminating other stressors will be an important factor in increasing coral survival

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.



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.