Photo: Steve Lindfield

Chapter 5

Vulnerability of coral reefs in the tropical Pacific to climate change

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'Temperature-related effects of global warming on coral reefs are highly visible, well-defined and extensively documented. The more recently recognised effects of atmospheric carbon dioxide on ocean acidification will have even more profoundly detrimental long-term effects on reefs.' (Veron et al. 2009)[i]

i Veron et al. (2009) The coral reef crisis: The critical importance of < 350 ppm CO_2. *Marine Pollution Bulletin* 58, 1428–1436.

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5.1 Introduction

Coral reefs are one of the dominant features of the tropical Pacific Ocean, proliferating in shallow, nearshore environments where sediment and nutrient concentrations are generally low. Coral reefs form complex habitats that provide critically important ecological services such as food, resources for livelihoods and coastal protection[1–3]. They are also culturally significant and play a central role in the lives of the Melanesian, Micronesian and Polynesian peoples of the Pacific[4,5].

Corals and a number of other calcifying organisms (e.g. crustose coralline algae) build coral reefs, incorporating the abundant calcium carbonate from the surrounding waters within their tissues to create aragonite structures. Over time, the dead skeletons of these organisms accumulate, forming reefs and islands that provide habitat for thousands of species. Despite their importance, coral reefs are currently threatened by a wide range of local stressors, such as declining water quality, pollution, overexploitation and physical destruction[1,6], and global stressors, such as the warming of the planet and ocean acidification[7]. Ultimately, these changes threaten to destabilise reef-related livelihoods for hundreds of thousands of people throughout the region[8,9].

In this chapter, we assess the vulnerability of the coral reefs that underpin coastal fisheries and aquaculture in the tropical Pacific, by examining the possible effects of climate change on coral communities and other reef-building organisms. Our analysis draws on the projected changes to the surface climate and ocean of the tropical Pacific, described in Chapters 2 and 3, to quantify how coral reefs are likely to be exposed to these effects. The results of that analysis were used in the framework outlined in Chapter 1 to assess the vulnerability of coral reefs in the region under the Intergovernmental Panel on Climate Change (IPCC) B1 and A2 greenhouse gas emissions scenarios[10]. Given the demonstrated potential for local factors to amplify the effects of global climate change on coral reefs[7,11], factors operating at a local level are an important aspect of this analysis.

We set the scene by describing the structure and distribution of coral reefs in the tropical Pacific (25°N and 25°S, 130°E and 130°W), briefly explaining the vital role of coral reefs in supporting coastal fisheries and aquaculture in the region, and summarising the critical requirements for establishing and maintaining corals. We then outline how coral reefs have already been affected by the changing climate and assess the projected vulnerability of coral reefs to continuing climate change. The chapter focuses primarily on the effects of future changes to sea surface temperature (SST), solar radiation, ocean acidity, tropical storms and floods, sea-level rise, and ocean circulation and upwelling. We then integrate these assessments into projections for the structure and biological complexity of coral reefs under the B1 and A2 emissions scenarios for 2035 and 2100.

We conclude by identifying the remaining uncertainty and important gaps in knowledge, outlining the research required to fill these gaps, and summarising the key management responses needed to maintain the important role that coral reefs play in supporting coastal fisheries and aquaculture in the Pacific.

5.2 Structure and distribution of coral reefs in the tropical Pacific

The recent maps of coral reefs from Landsat 7 high resolution (30 m) remote sensing images[12], and the information from the new 'Atlas of Pacific Ocean Coral Reefs', provide the most up-to-date picture of the extent, structure and distribution of the various types of coral reefs within the 22 Pacific Island countries and territories (PICTs)[12,13].

The first major pattern to emerge from this information is that, for several PICTs in Micronesia and Polynesia, the areas of coral reef habitat greatly exceed the area of land (**Table 5.1**). The second is the hierarchy of diverse reef structures. At the apex of the hierarchy, the coral reefs of the region can be divided into 'continental' and 'oceanic' reefs (**Figure 5.1**). Continental reefs are defined by the geological origin of their underlying substrates[14–16], or the size of associated land masses, and are found only in Papua New Guinea (PNG), New Caledonia (on Grande Terre) and Fiji (on Viti Levu and Vanua Levu). All other reef areas in PICTs are considered to be oceanic.

Both continental and oceanic reefs include barrier reefs, fringing reefs and patch reefs, but also atolls and banks. However, the oceanic barrier, fringing and patch reefs are all attached to oceanic island reef complexes, whereas continental barrier, fringing and patch reefs are attached to the continent (**Figures 5.1** and **5.2**). As a sublevel in the hierarchy of continental reefs, continental islands and their associated reefs may also occur in close proximity to the continent (e.g. Belep Islands in New Caledonia). Atolls and banks are distinguished mainly by the presence/absence of a closing rim, and the degree to which their lagoons are closed. Islands differ from atolls and banks in that the land mass is not derived from carbonate sediments. Fringing reefs form around islands and continental masses, and vary in the way they are exposed to oceanic swells or positioned in lagoons and embayments. Barrier reefs are offshore structures, separated from the land by lagoons or large sedimentary terraces. Patch reefs are intertidal or subtidal constructions of varying sizes, which are not continuous (like barrier reefs) or adjacent to land (like fringing reefs). These broad reef types can be divided into finer levels (classes) of reef geomorphology, exposure and depth[17].

Several PICTs made up of oceanic reefs consist almost entirely of atolls (e.g. Marshall Islands, Kiribati, Tuvalu, Tokelau) (**Table 5.1**). Oceanic reef structures in some PICTs are dominated by fringing reefs directly exposed to ocean waves and runoff from high island land masses (e.g. Vanuatu). Most of the PICTs with oceanic reefs, however, have a range of islands, banks and atolls of various sizes (e.g. American Samoa, French Polynesia, Federated States of Micronesia (FSM), Palau, Niue, Wallis and Futuna). At the finest level (class) of reef geomorphology, there is great variation among PICTs, ranging from two classes of reef type in Nauru up to > 150 classes in New Caledonia, Fiji and PNG (**Table 5.1**).

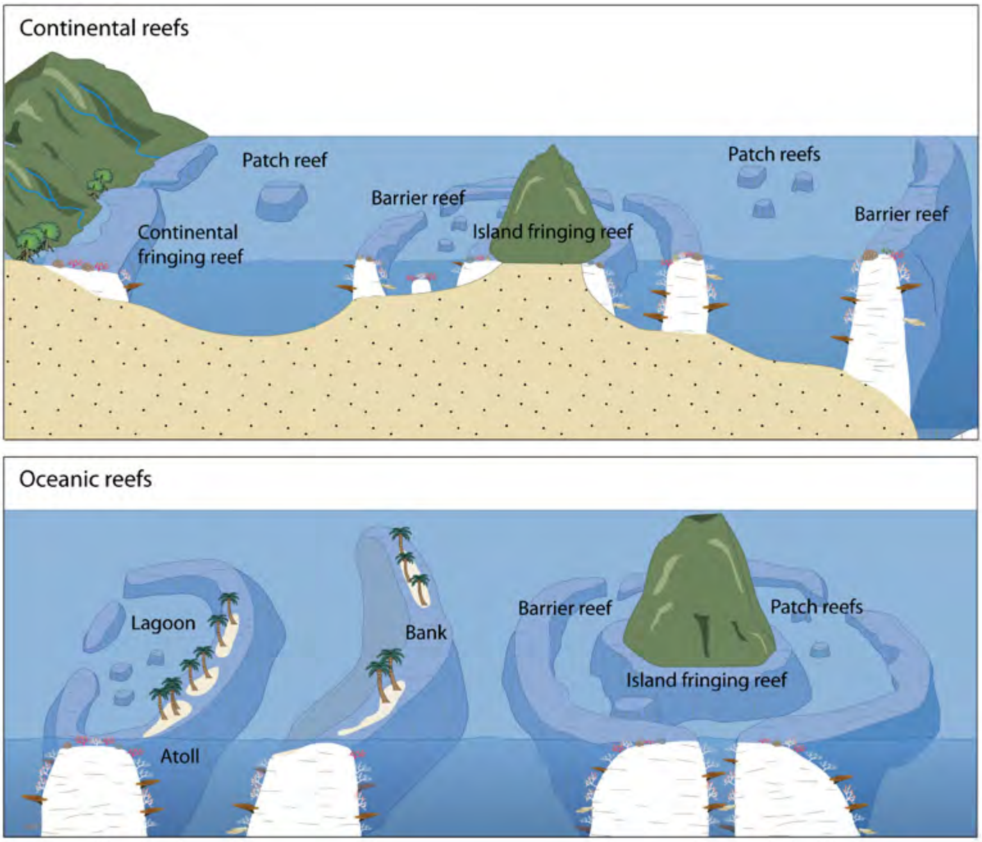


Figure 5.1 The main types of continental (connected to the mainland) and oceanic coral reefs.

This diversity of reef types is significant for PICTs because the various categories and classes of reef differ in their exposure and sensitivity to disturbance, and presumably also to the effects of climate change. The degree to which atolls are 'closed' is a pertinent example. The closed to semi-closed atolls found in the central Pacific differ from the open atolls of the western Pacific in their exposure and sensitivity to hydrodynamic change. Hydrodynamic regimes and average residence times of water in lagoons can easily be modified by sea level and wind/wave variations on short time scales, and presumably also by slowly shifting conditions[18,19]. Changes that switch semi-closed lagoonal waters from being replenished rapidly to being renewed slowly have led to planktonic algal blooms, anoxia and mass mortalities of fish and invertebrates[20,21].

Table 5.1 Total area (km^2) of land and coral reef, and areas of coral reef comprising atolls, banks and formations associated with islands, on Pacific Island countries and territories (PICTs). Values derived from Landsat 7 images and 'Atlas of Pacific Ocean Coral Reefs', except for Fiji and Papua New Guinea. Number of reef classes for each PICT is also shown.

PICT	Land	Total reef	Atoll[a]	Bank[b]	Island				No. reef classes
					Barrier reef	Patch reef	Fringing reef	Inter-reefal[c]	
Melanesia									
Fiji	18,272	10,000*	n/a	n/a	n/a	n/a	n/a	n/a	> 150
New Caledonia	19,100	35,925	15,466	413	3476	733	790	15,047	163
PNG	462,243	22,200*	n/a	n/a	n/a	n/a	n/a	n/a	> 150
Solomon Islands	27,556	8535	2191	599	1471	645	1328	2301	134
Vanuatu	11,880	1244	22	40	59	28	629	466	58
Micronesia									
FSM	700	15,074	11,859	420	523	21	212	2039	72
Guam	541	238	0	113	19	1	75	30	27
Kiribati	690	4320	3986	114	0	0	0	0	23
Marshall Islands	112	13,930	13,910	20	0	0	0	0	20
Nauru	21	7	7	0	0	0	0	0	3
CNMI	478	250	0	33	25	0	67	125	23
Palau	494	2496	555	17	615	86	163	1060	58
Polynesia									
American Samoa	197	368	11	9	5	0	47	296	16
Cook Islands	240	667	548	5	58	1	17	38	37
French Polynesia	3521	15,126	13,524	35	802	27	178	560	66
Niue	259	56	56	0	0	0	0	0	9
Pitcairn Islands	5	48	17	17	0	0	4	10	17
Samoa	2935	466	0	0	203	7	139	117	28
Tokelau	10	204	204	0	0	0	0	0	8
Tonga	699	5811	47	96	564	377	171	4556	70
Tuvalu	26	3175	3040	135	0	0	0	0	18
Wallis and Futuna	255	932	588	75	95	14	56	104	25

* Estimates only; a = area below high water mark, including 'drowned' atolls; b = small area below high water mark, including 'drowned' banks; c = includes lagoons and sedimentary areas within main island reef types; n/a = data not available.

Island size also affects the exposure of reefs to disturbance. Barrier reefs on large islands and continental land masses are more likely to be exposed to plumes of sediments from rivers compared with barrier reefs on small islands. Similarly, fringing reefs surrounding large land masses are more likely to be affected by floods and rainfall than barrier reefs.

Overall, the location, spatial organisation and fragmentation of coral reefs influence their resilience to perturbations. In particular, reefs on small, isolated islands are less likely to be resilient than those on well-connected islands that receive larval coral recruits from a variety of sources. On larger islands, the main threats to the resilience of coral reefs are land-based sediments and pollution.

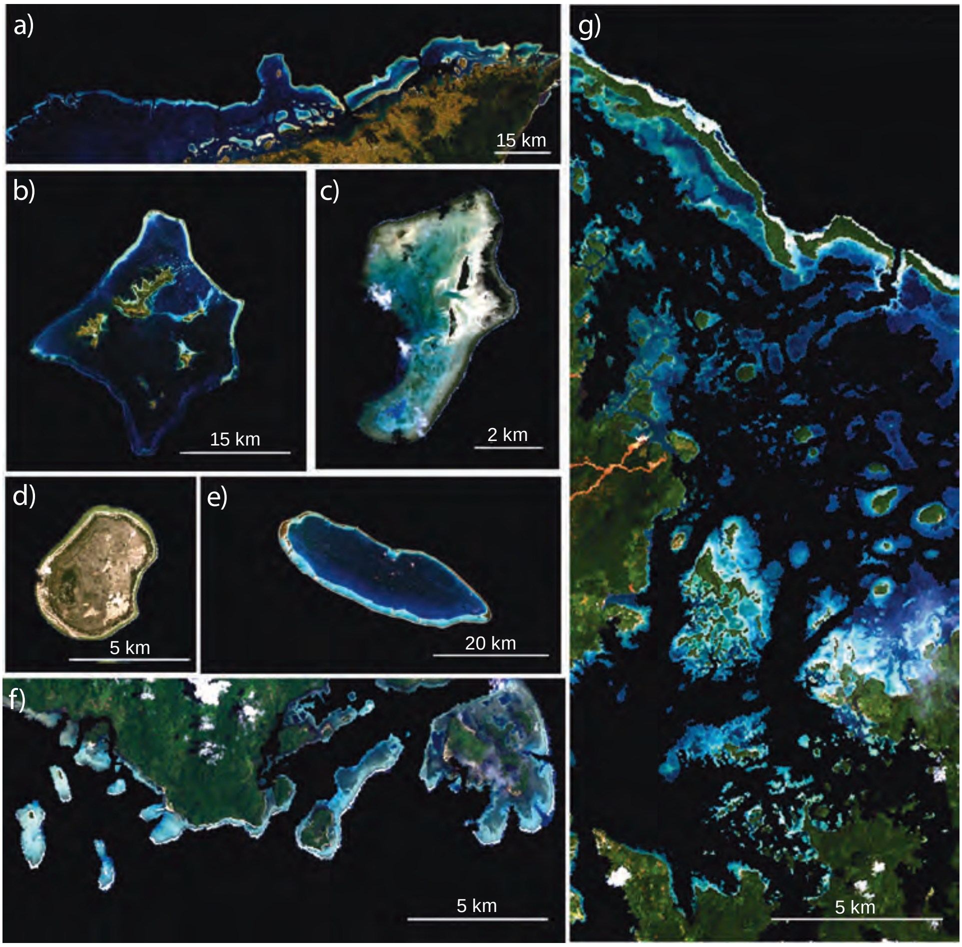


Figure 5.2 Examples of the main coral reef types in the tropical Pacific Ocean: (a) continental barrier reef, protecting lagoonal patch and fringing reefs (Vanua Levu Island, Fiji); (b) oceanic barrier reef surrounding a lagoon with fringing and patch reefs (Mangareva, French Polynesia); (c) oceanic reef island bank (Malekula Island, Vanuatu); (d) oceanic atoll that has been uplifted with a narrow fringing reef (Nauru); (e) closed oceanic atoll (Kaukura atoll, French Polynesia); (f) fringing and patch reefs around an oceanic island (Malekula Island, Vanuatu); (g) lagoonal patch and fringing reefs (Vangunu Island, Solomon Islands).

Regardless of reef size, type and orientation, the location of a reef can also be expected to influence the extent of disturbances. Because the southern barrier reef in New Caledonia is located near an area of strong and frequent upwelling, for example, it is less likely than barrier reefs in Fiji or PNG to be exposed to thermal stress from rising SST[22]. Similarly, reefs located at depths of 30 m or more are unlikely to be severely affected by increases in SST and changes in sea level. Such reefs occur commonly between American Samoa and Tuvalu, and in FSM. Reef crests located in places flushed by oceanic waters often fare better than enclosed basin or lagoonal reef areas during periods of high water temperature associated with mass coral bleaching events[23].

The location of reef classes within reef types also determines exposure and sensitivity. For example, because the fore-reef receives the greatest amount of wave energy, the corals there grow faster due to the high rate of water movement, and hence nutrient and gas exchange. Differences in light intensity can also have large influences on the extent of coral bleaching and mortality[24,25], with high islands sometimes shading coral reefs and reducing stress, as seen in Palau during 1998[26]. Reef flats and terraces are usually sheltered from wave action and have conditions suitable for growth of diverse coral communities. However, reef flats, shallow fore-reefs, and reticulated areas are more susceptible to physical destruction by tropical cyclones than deep areas of fore-reefs and lagoons[27]. Also, reef crests and high energy reef flats create environments conducive for crustose coralline algae, which are susceptible to changes in the pH of sea water[28].

In summary, reef types and classes differ in their exposure and sensitivity to disturbance, often depending on their location. Consequently, PICTs with a large variety of reef structures and types are likely to cope better with the impacts of climate change than those with a limited diversity of reefs.

5.3 Role of coral reefs in supporting fisheries in the tropical Pacific

Coral reefs are the dominant and most readily accessible coastal habitats in virtually all PICTs (**Table 5.1**), and support a wealth of fish and invertebrate species that are used for food and as a source of income. The role of coral reefs in providing food security across the tropical Pacific is significant – fish provide 50–90% of the animal protein in the diet of coastal communities in the region, with the majority of these fish caught by subsistence fishing on coral reef habitats[3,29–31]. The coastal fish and invertebrate resources of the tropical Pacific are harvested by the four types of fisheries described in Chapter 9 and summarised briefly here.

- **Fisheries for demersal fish:** Comprised of bottom-dwelling fish caught mainly near coral reefs using handlines, gill nets or by spearfishing. The extensive range of species caught are used mainly for food by households, or sold locally to earn or supplement incomes[30]. However, specialised fishing operations have occurred in the past in some PICTs to supply large carnivorous reef fish (mainly groupers) to the live reef fish trade[32,33]. A wide range of small colourful species are also caught for the tropical marine aquarium market[34,35].
- **Fisheries for nearshore pelagic fish:** Based largely on the stocks of skipjack and yellowfin tuna that support offshore industrial fishing fleets throughout much of the tropical Pacific (Chapter 8). However, these fisheries also capture significant quantities of other large pelagic species, such as Spanish mackerel, mahi-mahi, wahoo and rainbow runner, and a broad range of small pelagic species (flying fish, scads, mackerel, pilchards and anchovies). The larger species are generally caught by trolling along reef edges, but they are also increasingly targeted by fishing around anchored fish aggregating devices (FADs) deployed in nearshore waters

within ~ 10 km of the coast. Taken together, the large and small pelagic species contribute substantially to the food security and income earning opportunities of coastal communities throughout the region.

- **Fisheries for targeted invertebrates:** Focusing mainly on sea cucumbers and trochus (but also giant clams, spiny lobsters, crabs and green snail), which have long been an important source of revenue for coastal communities[36]. Many of these species are associated mainly with coral reefs and are harvested by specialised fishing operations. Sea cucumbers and trochus, in particular, have been fished extensively throughout the tropical Pacific for more than a hundred years, and exports of the non-perishable, dried product (bêche-de-mer) from sea cucumbers[37], and trochus shells, enable even remote communities to earn income[30,35]. The ease of collecting these invertebrate species, and their high market value, has led to widespread overfishing in the region[35,37]. Spiny lobsters, once collected opportunistically by free divers, are now the target of commercial fisheries based on the use of underwater torches and SCUBA.
- **Fisheries for shallow subtidal and intertidal invertebrates:** Involving the 'gleaning' of a wide range of molluscs (giant clams, other bivalves, gastropods and octopus) and echinoderms (sea cucumbers and urchins) from coastal areas at low tide. These animals are often collected by women and children, and provide an important source of household food, especially when weather conditions prevent other fishing activities. This fishery is an integral part of the social fabric in many PICTs.

Apart from nearshore pelagic operations, all sectors of coastal fisheries are fundamentally dependent on healthy coral reefs. Many species of fish and invertebrates are found only on coral reefs and, in general, reefs with a wide variety of coral formations, and therefore high topographic complexity, support a greater abundance and diversity of reef-associated fauna[38]. Populations of fish and invertebrates associated exclusively with coral reef habitats are typically highly dependent on the complex biological and physical structure created by scleractinian corals. Such populations decline in abundance dramatically after extensive loss or degradation of coral caused by temperature-induced coral bleaching and other environmental impacts, such as tropical cyclones[38–41].

Some fish and invertebrates rely directly on live corals for food, shelter or recruitment, although many of these species (e.g. butterflyfish) are not generally harvested[39]. However, corals are important contributors to primary production on reefs, and decreases in coral abundance may lead to reduced energy transfer to higher trophic levels in ways that could affect important fisheries species[42]. The growth and calcification of reef-building corals and crustose coralline algae need to exceed the losses caused by physical and biological erosion, which may take away as much as 90% of the calcium carbonate laid down by these calcifying organisms[7]. Otherwise, the complex reef frameworks crumble and disintegrate over time, with profound implications for the productivity of coastal fisheries and reef-based tourism.

Human settlements have also had a strong impact on coral reef habitats throughout the tropical Pacific. As human population densities increase, fishing activity becomes more intense and diverse[29,30,43] (**Figure 5.3**), with the effect that ecologically important species such as large predatory, and herbivorous fish, are targeted and depleted (Chapter 9). Other activities, such as pollution, sediment and nutrient inputs, dumping of rubbish and careless anchoring of boats can lead to localised damage to the structural complexity of coral reefs. Collectively, the diverse local effects in many PICTs and other developing countries have led to a 'coral reef crisis'[6] – a reduction in corals, and a rise in the relative dominance of other organisms such as soft corals and seaweeds. Altered reef frameworks and ecological functions in turn lead to reefs that support lower populations of fish and invertebrates important for food and income (**Figure 5.3**). Overcoming this crisis is not straightforward, particularly in developing countries[44], and requires innovative management to prevent the damage occurring in the first place and to provide incentives for restoration.

Fishing can also affect sharks, which often have a special importance and value to tourism. In countries such as French Polynesia, good populations of sharks are attractive to SCUBA divers, and provide a critical advantage for particular locations in competitive tourism markets[45,46].

5.4 Critical requirements for coral reefs

Given the importance of reef-building corals to reef structures, it is important to understand the conditions corals need for their establishment and growth, and how they are likely to respond to climate change. In the Pacific, corals that build reefs are found in warm, alkaline and sunlit waters between latitudes 30°N and 30°S. In these locations, reef-building corals accumulate calcium carbonate (as calcite or aragonite), with their skeletons growing to form the key structural components of coral reefs, glued together by chemical precipitation and by other marine calcifiers, such as crustose coralline algae. Spaces within the coral framework are then filled in by sand and the calcareous skeletons of green algae, such as *Halimeda* spp., and foraminifera, sponges, molluscs and crustaceans. Over time, this accumulation of organisms and their skeletons prevails against the forces of physical, chemical and biological erosion, and reef structures build up. Eventually, complex three-dimensional reef structures are created, which form the habitats for the many fish and invertebrates that provide food security and livelihoods across the tropical Pacific.

The environments in which coral reefs prosper have been explored using a database of the physical and chemical conditions for locations where reefs occur[47]. This analysis showed that corals require SST above ~ 18°C, ample light, and aragonite saturation states > 3.3 (a measure of the amount of calcium and carbonate in the water column relative to the precipitation point of aragonite – a form of calcium carbonate).

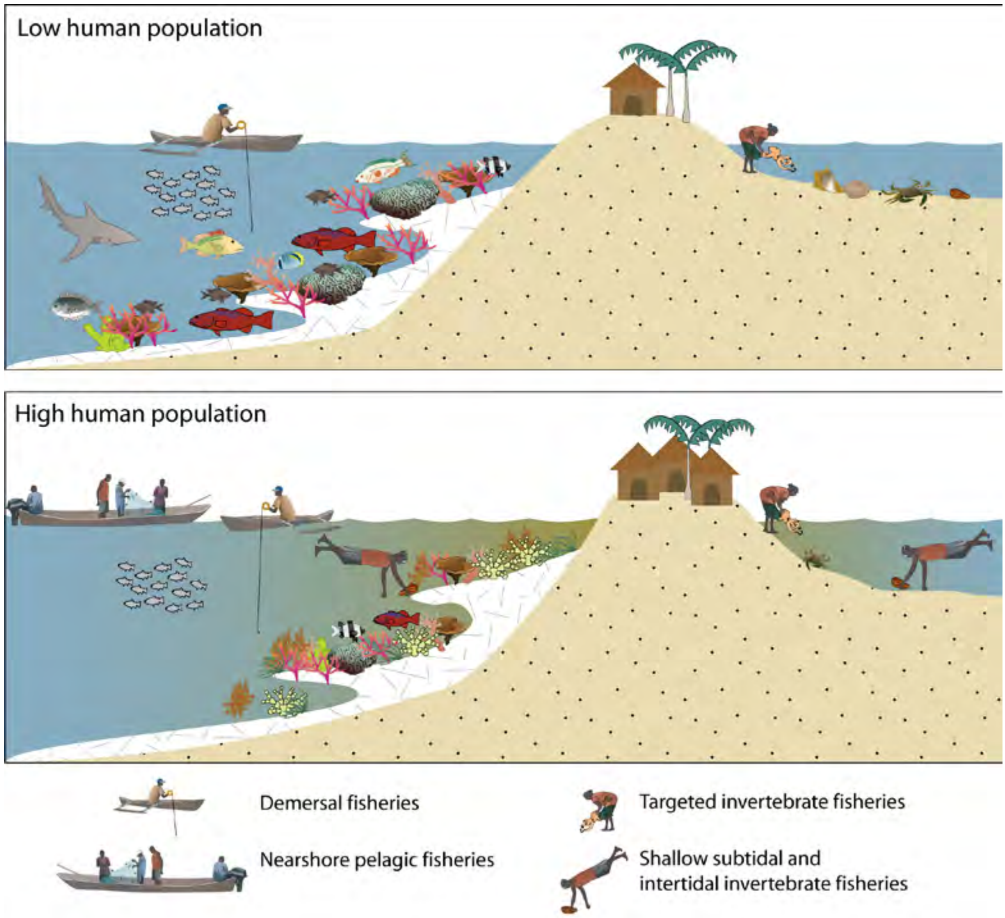


Figure 5.3 Common coastal fisheries activities in the tropical Pacific for demersal fish, nearshore pelagic fish, invertebrates targeted for export and shallow subtidal and intertidal invertebrates which occur on/or near coral reefs. In areas with low human populations, reefs have a greater abundance of reef-building corals and associated fauna. As human populations increase, fisheries resources decrease and reef ecosystems shift towards a mixture of seaweeds and corals, with seaweeds increasing as human activities become more intense. Lower numbers of demersal fish cause people to focus on other resources, such as gleaning invertebrates from shallow subtidal and intertidal areas, and nearshore pelagic fish.

While SST, light and concentrations of carbonate ions are the most important variables determining the formation of coral reefs, other factors such as river runoff, low salinity events and storms also influence the development of reefs. Large rivers often deliver substantial amounts of fresh water, nutrients and sediments to coral reefs, especially where catchments have been disturbed by agriculture, mining and deforestation (Chapter 7). In some cases, corals have been lost in the receiving waters of such catchments[48,49]. Severe rainfall events can lead to local flooding and drainage reductions in salinity, ultimately killing corals and other coral reef organisms. In the parts of the tropical Pacific prone to cyclones, reefs are also damaged by storm surges, which break corals, shift sand, and destroy reef structures. The effects of runoff, salinity and severe storms can also interact. For example, coral reefs affected by coastal runoff may not calcify as fast as those in clear and well-mixed waters, and may be more susceptible to (or take longer to recover from) wave damage. Sometimes greater amounts of particles in the water column may increase the food resources for bioeroders, leading to potentially higher erosion rates. These interactions have the potential to combine with other stresses, such as overfishing, to produce sudden changes (phase shifts) in the structure of coral reefs and the animal and plant communities associated with them[50,51].

5.5 Coral reefs in a changing world

There is growing evidence that the structure and ecological function of coral reefs are undergoing some major changes due to local and global stressors. Studies of coral reefs in the tropical Pacific and Southeast Asia show that the percentage of coral cover in 2007 was only about half that of the early 1980s[52]. This decline suggests that coral reefs are losing their dominant coral populations at about 1–2% per year. Interestingly, coral loss has occurred not only in areas, such as Southeast Asia, under pressure from local factors, but has also been observed in some well-managed regions, such as the inshore Great Barrier Reef. A systematic survey by the Australian Institute of Marine Science showed that although coral cover on offshore reefs of the Great Barrier Reef has not declined at the same rate as on inshore reefs, growth and calcification has slowed significantly (around 15% since 1990) in long-lived *Porites* colonies across the entire Great Barrier Reef [53]. This study suggests that ocean warming and acidification are beginning to play a greater role in the demise of coral reefs than local factors, such as water quality, destructive practices and overfishing.

5.5.1 Effects of global warming on coral reefs in the tropical Pacific

One of the key characteristics of reef-building corals is their mutualistic symbiosis with populations of dinoflagellates (*Symbiodinium*). These tiny plant-like organisms occupy vacuoles within cells associated with the gastrodermal tissues of corals, imparting an overall brown colour to their animal host (**Figure 5.4**). *Symbiodinium* photosynthesise while they are resident within the cells of the host coral, and produce abundant organic carbon. This carbon is transferred to the coral, where it powers growth, reproduction and calcification. As a result of this abundant energy, corals are able to grow and calcify rapidly, providing in return much-needed inorganic nutrients to *Symbiodinium*, and calcium carbonate to the reef community[54].

The symbiosis between corals and *Symbiodinium* breaks down under stressful situations. Sudden reductions in salinity, or increases in chemical toxins, SST or solar irradiance, will cause corals to turn brilliant white, as the brown *Symbiodinium* cells leave their tissues[24]. This phenomenon is referred to as coral bleaching (**Figure 5.4**). Deprived of their energy source, corals become much more susceptible to competitors, such as macroalgae (seaweeds), starvation, disease and death[52,55–57].

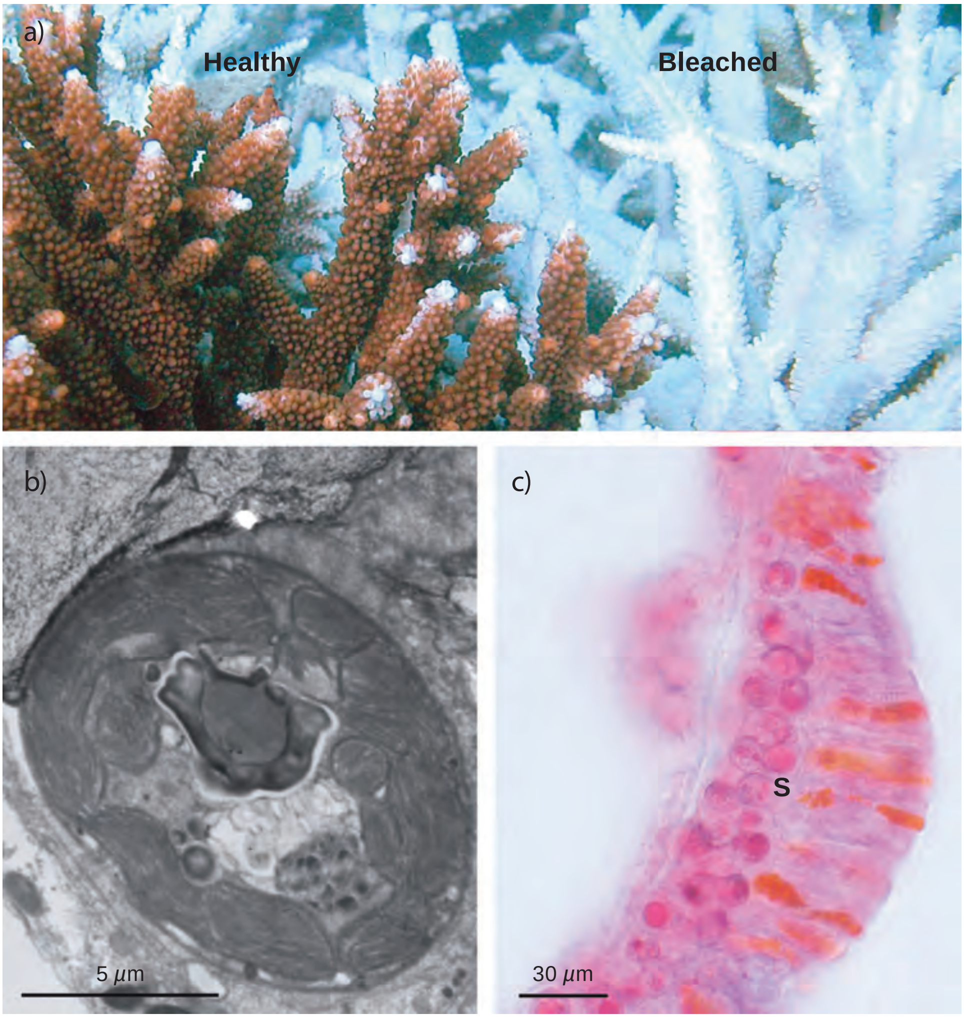


Figure 5.4 Corals, dinoflagellates and coral bleaching: (a) normally pigmented corals (*Acropora*) shown alongside bleached corals; (b) transmission electron micrograph of a single dinoflagellate symbiont (*Symbiodinium*); (c) light micrograph of dinoflagellate symbionts (S) residing within the gastrodermis of a coral polyp (photos: Ove Hoegh-Guldberg).

Coral bleaching has been reported on a local scale (small patches of reef or communities of corals) for around 80 years[58]. Starting in the early 1980s, however, entire coral reefs and regions began to experience 'mass' coral bleaching. Investigation of the environmental factors associated with mass coral bleaching soon revealed a strong causal link to periods of elevated SST, which were often correlated with doldrum-like conditions where seas were both warm and still. Elevated SST destabilises the symbiosis of corals and *Symbiodinium*, resulting in a dramatic decline in the population density of *Symbiodinium* in coral tissues[59–62].

Measurement of SST anomalies by satellites reveals strong correlations between coral bleaching, and periods when SST exceeds the summer maxima by 1–2°C for 3–4 weeks or more, especially during strong El Niño events[63,64]. The extent of mass bleaching and mortality increases as the thermal anomalies in SST intensify and lengthen[24,65]. On a smaller scale, patchiness in bleaching due to local ecological and environmental variability complicates the interpretation to some extent[66,67].

Coral bleaching has affected coral reefs in the tropical Pacific a number of times since large-scale events were first reported in the early 1980s. In each of these worldwide events, coral reefs in the region experienced high levels of mortality, albeit lower than those recorded in the western Indian Ocean, when about 46% of corals perished in 1998[68]. Projections of how SST is likely to change, however, suggest that these conditions could occur more frequently on coral reefs in the tropical Pacific over the coming decades[7,24,69,70]. In September 2010, tropical SSTs were the warmest on the instrumental record and were widespread, with extensive coral bleaching being reported in Southeast Asia and the Caribbean, among other regions. Sea surface temperatures are rising in the tropical Pacific at rates of change which exceed even the fastest rates estimated to have occurred over the past 420,000 years[7] (Chapters 2 and 3).

5.5.2 Additional effects of ocean acidification

About 25% of the extra carbon dioxide (CO_2) injected by human activities into the atmosphere is eventually absorbed by the oceans[71] (Chapter 3). On entry, CO_2 reacts with sea water to create dilute carbonic acid, which interacts with carbonate ions, turning them into bicarbonate ions[72] (**Figure 5.5**) (Chapter 3). The net effect of this process, known as ocean acidification, is a sharp decline in concentration of carbonate ions. Because of the importance of carbonate ions for reef calcification, this change results in a significant reduction in the calcification rate of reef-building corals and other calcifying organisms[73]. Considerable experimental and field evidence indicates that corals may not calcify rapidly enough to keep pace with physical and biological erosion if exposed to aragonite saturation states < 3.3[7,73].

As mentioned in Section 5.3, coral reefs represent a balance between reef calcification (by corals and other calcifiers such as crustose coralline algae) and erosion (by storms, dissolution and biological eroders). If the balance is tipped in favour of erosion, there will be a loss of reef structure and integrity over time. There is generally a close balance between calcification and erosion, with much of the calcium carbonate (> 90%) laid down being removed by biological and physical processes[74]. The precise relationship between reef calcification and erosion, however, depends on a number of factors such as water quality, location and latitude.

There is already considerable evidence that corals on the Great Barrier Reef[53,75] and in Thailand[76] are calcifying at rates that are ~ 15% lower than those before 1990. Importantly, this decrease in calcification was unprecedented in the 400 years of records examined for the Great Barrier Reef. As well as declining calcification rates, reduced carbonate ion concentrations are likely to increase the rate of biological

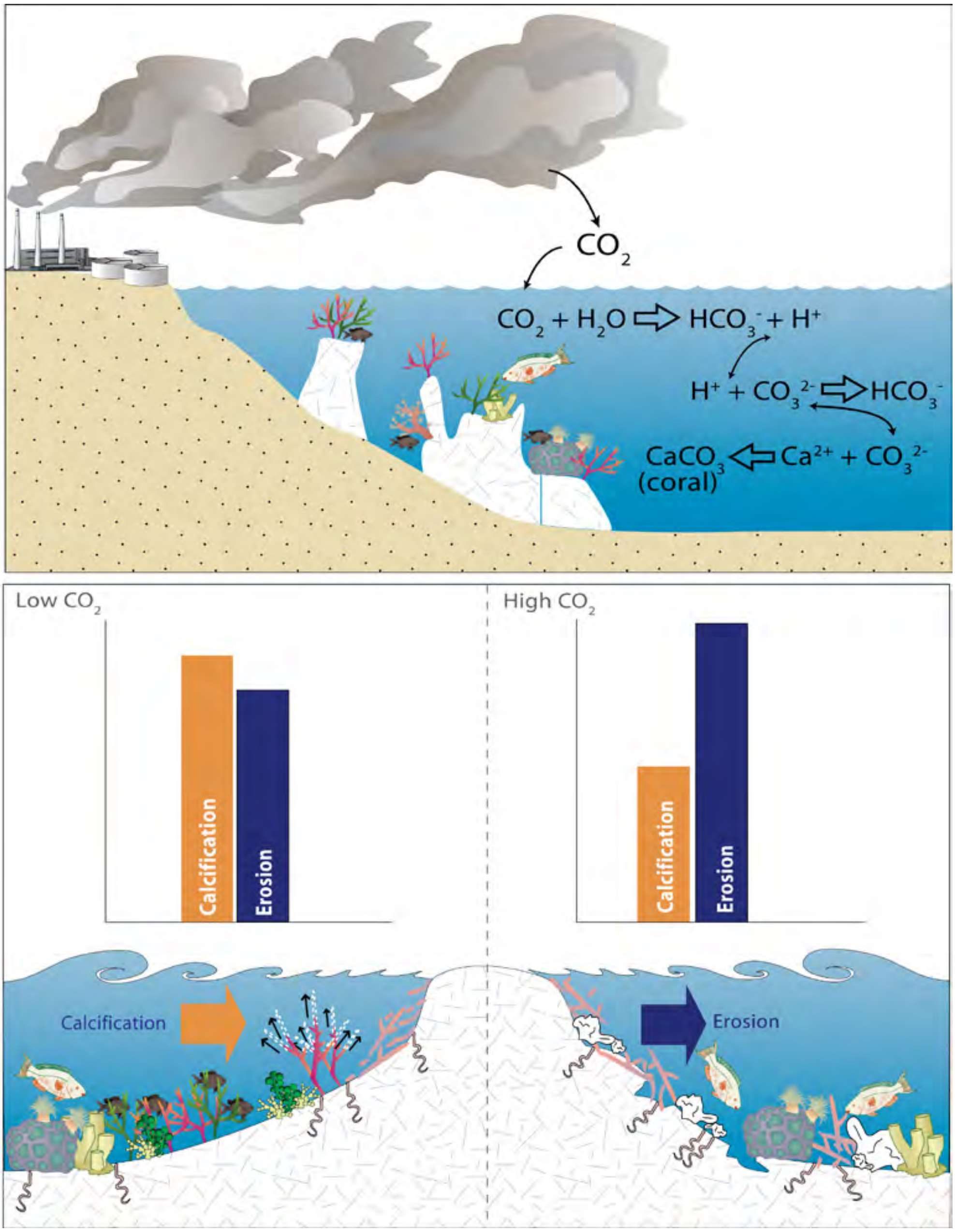


Figure 5.5 Ocean acidification is threatening reef-building corals. Carbon dioxide (CO_2) from the burning of fossil fuels is entering the ocean at greater rates and is reacting with water to produce a weak carbonic acid (upper panel). This reduces the concentration of carbonate ions, and makes fewer of them available for coral calcification (see Chapter 3 for more details). On healthy coral reefs under low atmospheric concentrations of CO_2, calcification by reef-building corals and calcareous algae usually exceeds erosion caused by wave action and biological eroders, such as boring worms, and grazing fish and invertebrates (lower panel). Under such conditions, reefs grow over time. But as CO_2 accumulates in the atmosphere, calcification is expected to decrease below the rates of erosion, with the net loss of reef frameworks over time.

erosion (via reduced density of coral skeletons and increased dissolution) favouring the activities of external bioeroders (e.g. fish and sea urchins) as well as internal bio-eroders that bore into skeletons (e.g. worms and sponges)[77–79].

5.5.3 Interactions and synergies

The combination of ocean acidification with other factors that stress corals may also lead to compounding effects. For example, the thermal threshold at which some corals bleach decreases when they are exposed to more acidic conditions[80]. The combination of high SST and increased acidity also leads to a more dramatic loss of coral reef productivity than if each factor acts on its own[80]. There are also likely to be a number of surprises given the complexity of the situation. A potential concern is that coral communities and skeletons weakened by bleaching and ocean acidification could be damaged more severely by more intense storms if they eventuate (Chapter 2), leading to accelerated degradation of reef frameworks.

Interactions between local factors, such as poor water quality and overexploitation of key reef species, and ocean warming and acidification, could also lead to synergistic and accelerated impacts. Crustose coralline algae, for example, play a crucial role within reef habitats as a settlement cue for a large number of invertebrates (including corals) and plants. Recent evidence has suggested that crustose coralline algae may be highly vulnerable to ocean acidification[80], thereby potentially leading to negative impacts on the settlement of corals and other reef-associated organisms, such as sea urchins[28]. Similarly, corals exposed to nutrients, sediments or pathogens are more susceptible to thermal bleaching, and less able to survive a bleaching episode[81]. While the precise details of these interactions remain to be documented, they appear to have the potential to amplify the individual effects of global warming and ocean acidification, leading to a reduced ability of coral reefs to bounce back from catastrophic events (i.e. reduced resilience).

5.5.4 Changes to coral reefs over time

The fossil record provides a strong indication of the changes likely to occur to coral reefs under rapid global climate change[70]. In particular, it shows that the five mass-extinction events that occurred on the planet were associated with 'reef gaps', which typically lasted for at least 4 million years. Coral communities and their associated limestone deposition are more or less missing from the palaeontology record at these times[70]. There is also growing evidence that the major extinction events were accompanied by changes in atmospheric CO_2 which led to global warming and ocean acidification. Interestingly, all but one of the extinction events (during the Cretaceous-Tertiary period 65 million years ago) seem to have occurred at much slower rates of change in the Earth's atmosphere and oceans than those observed over the past 100 years[82]. These past climate events provide compelling reasons for limiting further build-up of CO_2 in the atmosphere.

Photo: Éric Clua

Healthy coral reefs are important fish habitats

5.6 Projected vulnerability of coral reefs to climate change

In this section, we explore the projected vulnerability of coral reefs in the tropical Pacific to a changing climate. The approach we use to assess vulnerability is described in Chapter 1. This vulnerability framework integrates the exposure of coral reefs to climate change with their sensitivity to these changes, and provides a measure of the potential impact which may or may not be reduced through the putative adaptive capacity of corals and other key components of coral reefs. The same set of variables that determine the vulnerability of coral reefs have been assessed for the Great Barrier Reef[81,83,84], where the changes appear to be occurring at rates which are 100–1000 times faster than ice age transitions[7], outstripping the ability of corals and their *Symbiodinium* to keep pace. There is also concern that coral reefs in the tropical Pacific are unlikely to have the capacity to adapt to the high rates of change in their environment.

5.6.1 Sea surface temperature

Exposure and sensitivity

The average annual SST across the tropical Pacific increased by 0.23°C between 1989 and 2008, relative to average annual SST between 1950 and 1969 (Chapter 2). SST is projected to increase by 0.5–1.0°C in 2035 under the B1 and A2 emissions scenarios, by 1.0–1.5°C under B1 in 2100, and by 2.5–3.0°C under A2 in 2100, relative to SST between 1980 and 1999 (Chapters 2 and 3).

As discussed in Section 5.5.1, reef-building corals are very sensitive to these levels of warming, although there are some limited differences in thermal sensitivity between types of corals, and among *Symbiodinium*. The exposure and sensitivity of corals to rising SST have already had large-scale influences on reefs in the tropical Pacific and elsewhere in the world, with coral cover declining globally by 1–2% per year[52]. As outlined below, rising SST is expected to have further impacts on coral reefs.

Potential impact and adaptive capacity

As SST increases, reefs will continue to lose coral cover and may ultimately become dominated by macroalgae (**Figure 5.6**). The impact on corals can be expected to vary among species. Indeed, this is already happening under present-day temperature and bleaching regimes, which are causing changes in the species composition and structure of coral communities[85]. In particular, differential sensitivity to thermal stress between coral genera[86–88] is leading to shifts towards the more tolerant species[89]. However, because the differences in sensitivity between genera are generally limited to no more than about 2–3°C, shifts in coral communities are expected to be characteristic only of the next couple of decades. If SST increases beyond 2°C above preindustrial levels, most species of coral are likely to be rare on tropical reefs[7,24,81,90,91].

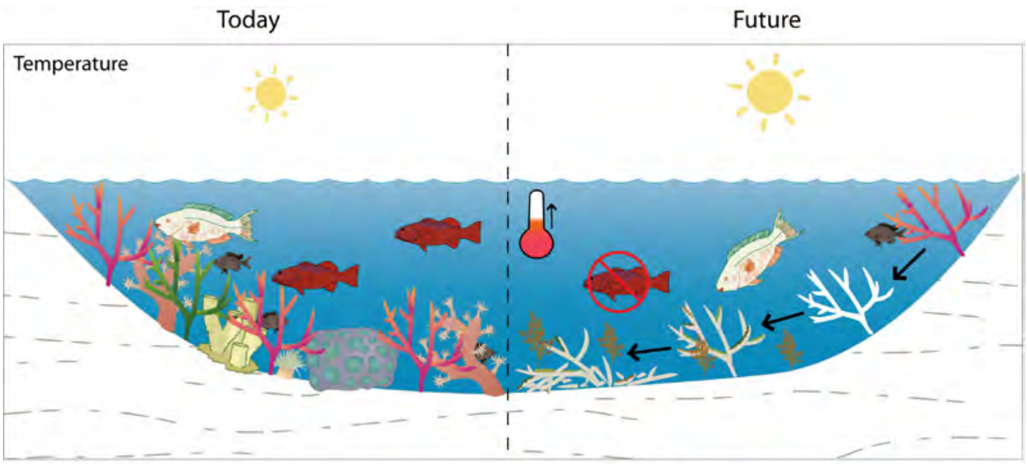


Figure 5.6 Effects of projected increases in sea surface temperature (SST) and light on coral reefs. Under present-day conditions, short periods of warmer-than-average maximum SST cause bleaching events. Healthy coral reefs recover from these disturbances and the abundance of corals remains high. As SST increases by 1°C or more above preindustrial levels, bleaching events are expected to become more intense and frequent, with the loss of corals, reef structure, and associated fauna, and increases in macroalgae, over time.

In addition to the greater tolerance to higher SST, some coral species appear to have some additional capacity to adapt to warmer waters. A few colonies within some populations of the coral *Acropora millipora* can increase the proportion of more temperature tolerant *Symbiodinium* in their tissues[92]. However, this strategy appears to provide an added tolerance to higher SST of up to only 1.5°C, and few of the colonies involved actually survived extreme heat stress. Furthermore, the cost that corals have to pay for such increased temperature tolerance may be slower growth, which is likely to have other negative ecological implications. Thus, this potential adaptive mechanism, called 'symbiont shuffling', is unlikely to protect reefs from the severe and repeated damage projected to occur due to rapid increases in SST.

There has been some discussion about the potential for coral populations to expand their distributions to higher latitudes as these areas begin to warm[24]. Such shifts have been reported in the palaeontological record, when coral communities extended their range by about 100 km in a poleward direction during periods when SST was slightly higher[93]. Nevertheless, there are limits to how far north or south coral populations can shift due to the decrease in pH and carbonate ion concentrations towards the poles. Projected increases in atmospheric CO_2 above 450 ppm are also expected to lead to contraction of suitable conditions for the growth of coral to the small band around the equator[7] (Section 5.6.3). In short, although waters at higher latitudes are expected to be warmer, corals will be unable to adapt by moving poleward.

Vulnerability

All existing information leads to the conclusion that coral reefs have very high vulnerability to further increases in SST, and the projected increase in SST in the tropical Pacific region of 1–3°C by 2100 will strongly influence the structure and function of coral reefs. Effects are expected to be clearly evident by 2035, but given the similarity in projected SST between the B1 and A2 emissions scenarios in 2035 (Chapters 2 and 3), there is little or no difference in the vulnerability of coral reefs to changes in SST under these two scenarios in the shorter term.

5.6.2 Solar radiation

Exposure and sensitivity

Global climate change is altering, and is likely to continue to alter, the weather and general circulation patterns, as outlined in Chapter 2. As a result, the distribution of clouds is likely to change, potentially affecting the amount of solar radiation reaching coral reefs. Climate change is also expected to result in an increase in rainfall in equatorial areas, and a decrease in rainfall in the southwest and southeast Pacific (Chapter 2).

Coral reefs are sensitive to both photosynthetically active radiation (PAR) and ultraviolet radiation (UVR). High levels of PAR will exacerbate coral bleaching[24,94], whereas high levels of UVR have the potential to increase damage to cellular components such as DNA. Sunlit waters without currents and waves amplify the effect of thermal stress on corals. In contrast, shading by high islands[95,96] or unusually cloudy conditions[25] reduces the effect of thermal stress on coral reefs.

Potential impact and adaptive capacity

Within limits, corals have some capacity to adapt to both high and variable PAR and UVR[97]. Acclimation takes between five and ten days, during which time the coral remains physiologically stressed. Corals can also acclimate to lower light levels in turbid waters, with turbidity potentially protecting them from bleaching[26]. The events causing turbidity (e.g. heavy rainfall and strong winds), however, appear to be unlikely to occur during the hot and still conditions that result in higher levels of irradiance. Turbidity is also likely to play a more important role in coastal areas where sediments and nutrients (and associated phytoplankton blooms) may reduce irradiance during stressful periods.

Vulnerability

On the basis of the capacity of corals to photo-acclimate within days, coral reefs appear to have a relatively low vulnerability to the changes in solar radiation expected to occur under either the B1 or A2 scenarios over the coming decades and century.

5.6.3 Ocean acidification

Exposure and sensitivity

As with SST, the current rates of change in atmospheric CO_2 and ocean acidification are believed to be more rapid than during any other period in at least the past 420,000 years[7] (Chapter 3). Ocean pH has already decreased by 0.1 units (representing a 26% increase in hydrogen ions) since the start of the industrial era and will continue to decrease as long as the oceans continue to absorb the increasing concentrations of CO_2 in the atmosphere (Chapter 3). Under the A2 emissions scenario, the aragonite saturation state in tropical surface waters is projected to decrease to 2.4 in 2100 (Chapter 3).

These projected changes will be hostile to coral reefs because the rate of calcification of corals and crustose coralline algae is highly sensitive to declining carbonate ion concentrations[73]. Furthermore, processes such as bioerosion are likely to increase as the concentration of carbonate ions decreases (**Figure 5.7**). Indeed, the current distribution of corals, together with experimental investigations and now field evidence, indicates that the ability of corals and other marine calcifiers to maintain a positive reef carbonate balance falls into deficit when atmospheric concentrations of CO_2 exceed 450 ppm (which translates to carbonate ion concentrations of ~ 200 μmol per kg of sea water at equilibrium). There is also considerable evidence that concentrations of CO_2 above 350 ppm may be too much for the maintenance of carbonate coral reef systems[70].

Potential impact and adaptive capacity

Experimental studies[73] and field studies[53,75,76] indicate that substantial decreases in calcification can be expected to result in more fragile and degraded reef frameworks. There is little evidence of calcifying organisms adapting to the lower carbonate ion concentrations likely under ocean acidification. Indeed, although some temperate coccolithophores (a prominent member of the marine phytoplankton) may grow more quickly[98], corals and other tropical calcifying organisms are highly unlikely to be able to adapt at rates fast enough to keep up with the rapid acidification of the ocean projected under the A2 scenario (Chapter 3).

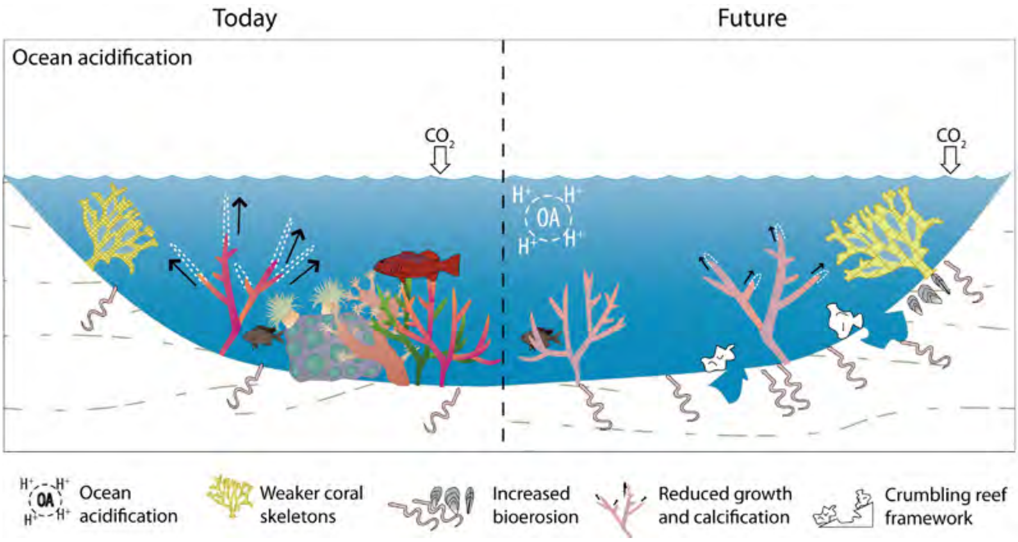


Figure 5.7 Effects of projected ocean acidification (OA) on coral reefs. The rising concentration of carbon dioxide (CO_2) in the atmosphere from the burning of fossil fuels is acidifying the world's oceans and decreasing concentrations of carbonate ions (Figure 5.5). Reduced calcification of reef-building corals and crustose coralline algae when CO_2 exceeds 450 ppm is expected to change the balance of reef processes from net construction to net erosion, leading to loss of corals and reef frameworks.

Vulnerability

The reduction in calcification rates at low carbonate ion concentrations suggests that corals, and the reefs they build, are highly vulnerable to ocean acidification, and that increases in atmospheric CO_2 above 450 ppm are likely to result in a negative carbonate balance (net erosion) of coral reefs throughout the tropical Pacific. This outcome will have important implications for ecological services, such as coastal fisheries (Chapter 9) and coastal protection.

5.6.4 Tropical cyclones and floods

Exposure and sensitivity

Warming of the tropical Pacific climate may gradually increase the intensity of tropical cyclones by 6–12%, equivalent to about half a cyclone category[99,100], over the remainder of the century (Chapter 2). Any such increases will have severe ecological implications because the energy dissipated by a cyclone increases as the cube of its maximum wind speed[101]. In equatorial regions, rainfall is projected to increase by 5–20% in 2035, and by 10–20% in 2100 (Chapter 2), increasing the likelihood of flooding.

Coral reefs are extremely sensitive to local physical damage caused by cyclones and storms because, as explained above, this damage escalates non-linearly with increasing maximum wind speed[102]. Reefs will be affected further by the low salinity, higher turbidity and nutrient-rich waters associated with floods caused by storms[49,103,104] (**Figure 5.8**). Damage from cyclones and storms may also trigger ecological 'phase shifts', especially when reefs are subject to overfishing of key functional groups[50].

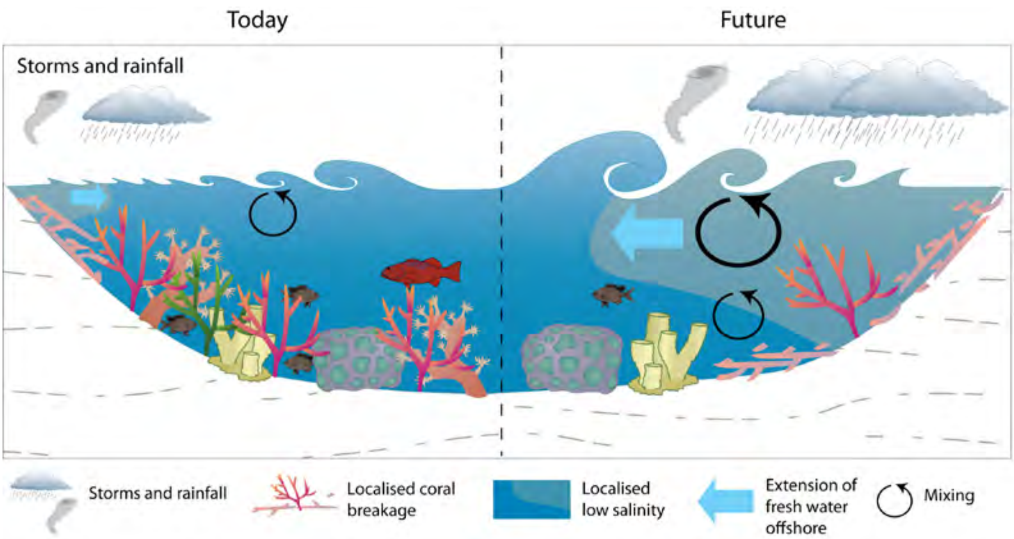


Figure 5.8 Effects of stronger cyclones and heavier rainfall on coral reefs, which are expected to lead to greater loss and degradation of habitat through damage by more powerful waves, reduced salinity and increased turbidity of coastal waters. The effects of stronger cyclones and increased rainfall are also expected to interact with higher sea surface temperatures (**Figure 5.6**), increased acidification (**Figure 5.7**) and local factors, such as poor catchment management, to cause severe problems for coral reefs.

Potential impact and adaptive capacity

There are numerous examples of the impact of cyclones and floods on coral reefs in the tropical Pacific, as well as evidence of recovery over periods stretching from 15–50 years. The effects of intensified cyclones are only just being studied, and can be hard to distinguish from background levels of damage from the normal range of storms. On the Great Barrier Reef, for example, a hypothetical increase in cyclone intensity by half a category is expected to result in a 50–60% increase in the loss of coral, and a substantial reduction in the structural complexity of reefs[102].

Projected changes to rainfall patterns may also lead to drying of coastal areas in the subtropical southeast and southwest Pacific, exacerbating the problem by loosening sediments and nutrients such that they are more easily washed out of coastal catchments during episodic high rainfall events (Chapter 7). More intense rainfall is also expected to exacerbate runoff from high islands in the equatorial Pacific.

There are strong regional differences in the past exposure of coral reefs to cyclones, with coral reefs in the northwest Pacific experiencing more and stronger cyclones than reefs south of the equator (Chapter 2). Coral communities exposed to storms are dominated by species with stout growth forms, and by fast-growing species, such as *Acropora* spp. These reefs have had thousands of years to adapt to local storm intensity. But no level of adaptation protects coral reefs from severe damage by category 4 or 5 cyclones.

Vulnerability

Coral reefs are expected to be moderately vulnerable to increasing cyclone intensities in their own right. Against the background of chronic stress from acidification, higher SST, unsustainable coastal land use practices and overexploitation of key functional groups, such as herbivores, more intense tropical cyclones could, however, also act as key agents for change in coral reef habitats. This compounding of threats can lead to sudden changes in ecological state[50], where any single factor could well cause the collapse of coral reefs.

5.6.5 Sea-level rise

Exposure and sensitivity

Average global sea-level rise has accelerated from 1.8 to 3.3 mm per year within the last century, and the rate is expected to increase with further thermal expansion of the ocean and melting of land ice[105,106] (Chapter 3). The unexpectedly rapid decline and thinning of Arctic sea ice (which does not affect sea level) and land-based polar ice sheets[107–109], shows that our current understanding of ice dynamics is still poor. Even so, research has shown that the western Antarctic ice sheet is breaking up much faster than projected, and that it has broken down at least 60 times over the past 5 million years when concentrations of CO_2 reached 400 ppm[110].

A significant threshold in the rate at which ice melts is expected to occur when average global temperatures are 2°C higher than preindustrial temperatures. At this point, temperatures above the Greenland ice sheet are projected to reach 3°C, which is considered the point at which rapid melting is likely to occur[110,111]. Based on this assumption, many experts recently agreed that sea level could rise by at least 1 m by the end of the century, with a possible possible rise of up to 2 m[112] (Chapter 3).

There is evidence that rapid sea-level rise over several decades has caused major, albeit short-lived, changes to coral reef communities and the structure of reefs due to rapid changes in depth, light and other factors such as wave stress[113]. However, sensitivity of coral reefs to future sea-level rise is expected to depend also on the influence of other factors on coral growth rate. In particular, reefs that are heavily stressed by global warming and ocean acidification are likely to be much more sensitive to sea-level rise. It is difficult to be more specific about the sensitivity of coral reefs to sea-level rise at this stage due to uncertainty about how sea level could change over the coming decades[106].

Potential impact and adaptive capacity

Healthy shallow-water corals can grow at rates which allow them to keep up with the current rate of sea-level rise and to colonise new areas. However, because significant increases in the rate of sea-level rise, over and above the conservative estimates reported by the IPCC[105], seem likely to occur by the end of this century, corals growing in marginal environments (e.g. low light or high latitudes, or in lagoons) may be unable to cope. This projection is supported by the fact that many reefs have 'drowned' throughout geological history. If thermal stress and ocean acidification inhibit the ability of corals to grow and calcify, rapid changes in the rate of sea-level rise may become a significant additional stress factor for coral reefs, even in shallow water (**Figure 5.9**).

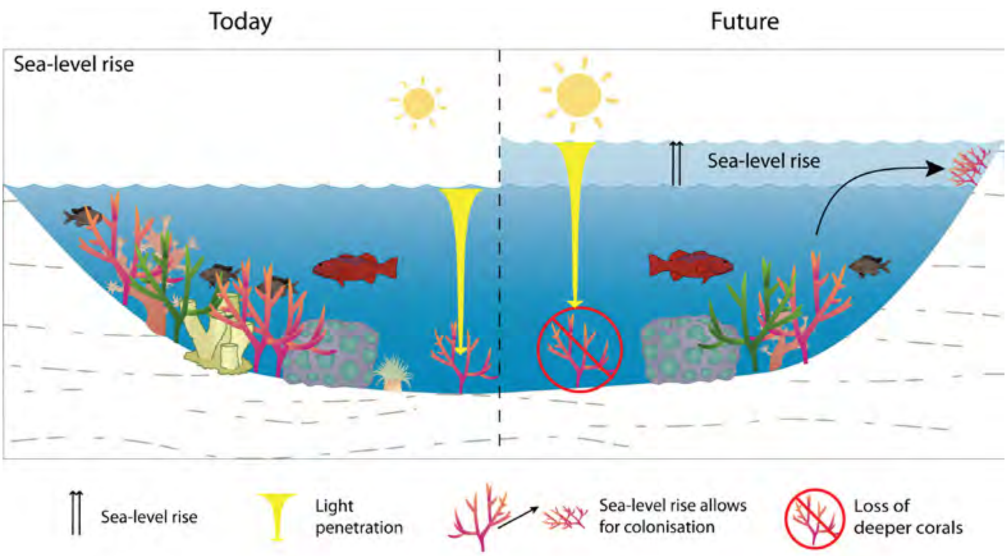


Figure 5.9 Effects of projected sea-level rise on coral reefs. Where corals and other reef building organisms are healthy, reefs should keep up with rising sea levels. Unfortunately, the combined effects of increased sea surface temperatures (**Figure 5.6**) and ocean acidity (**Figure 5.7**) are likely to mean that corals in some places will not grow fast enough to maintain their positions in the water column with the projected rapid sea-level rise. Some coral reefs may 'drown' as sea levels increase, but new areas may also be colonised where conditions for coral growth remain favourable.

Vulnerability

Coral reefs will vary in their vulnerability to sea-level rise. Corals with reduced growth rates due to thermal stress and ocean acidification, or corals with naturally slow growth rates in marginal environmental conditions (e.g. deeper water), may have a high vulnerability to the accelerating rise in sea level.

5.6.6 Ocean circulation and upwelling

Exposure and sensitivity

Ocean circulation patterns are important drivers of the productivity and function of coral reefs, and the connectivity of their populations[114]. The projected decreases in the strength of the equatorial branch of the South Equatorial Current (SEC) and the South Equatorial Counter Current (SECC), and alterations in the location and magnitude of upwellings resulting from these currents (Chapter 3), may therefore lead to changes in the genetic structure and connectivity of marine populations. By 2100, under the A2 scenario, the flow of the SECC is expected to decrease by up to 60%, and the SEC by ~ 20%.

Reductions in net primary production (NPP) and the density of zooplankton are also projected for all ecological provinces described for the tropical Pacific[115], except the Pacific Equatorial Divergence (Chapter 4). The decline in the availability of nutrients is expected to be greatest in the Archipelagic Deep Basins province[115], where NPP is projected to decrease by 20% in 2100 under the B1 emissions scenario, and by > 30% in 2100 under A2 relative to levels in 2000–2010 (Chapter 4). This ecological province includes Fiji, PNG, New Caledonia and Vanuatu, i.e. the PICTs with the vast majority of the population of the region.

Changes in currents have implications for the replenishment potential, and replenishment rate, of coral communities, and for fisheries management strategies, including the design of marine protected areas. Coral reef habitats are also highly sensitive to NPP, which in turn depends on mixing of the water column (Chapters 3 and 4). Increased stratification can be expected to lead to reduced access to nutrients by photosynthetic organisms in the photic zone, and reduced availability of food for organisms at higher trophic levels.

Potential impact and adaptive capacity

There are marked regional differences in oceanic currents, thermal stratification, upwelling and nutrient availability across the tropical Pacific[116] (Chapters 3 and 4). Although coral reefs and their associated organisms have adapted over many thousands of years to such environmental differences, decreases in NPP associated with stratification of the water column in tropical areas[117,118] (Chapter 4) have been associated with disturbances to organisms as diverse as fish, turtles and seabirds[119]. The relatively rapid changes to ocean circulation and upwelling, and the projected decreases in NPP, could lead to greater disruptions to the ecology of both phototrophic species (e.g. phytoplankton and seaweed) and heterotrophic species (e.g. fish and invertebrates) associated with coral reefs.

Vulnerability

Given the projected changes to the strength of the SEC and SECC, and the expected increases in nutrient-poor waters across much of the tropical Pacific (Chapters 3 and 4), coral reefs have a moderate vulnerability to changes in ocean circulation and upwelling as a result of climate change. Ultimately, the locations of coral reefs will have a strong effect on the extent of their vulnerability to changes in currents and upwelling – some will receive fewer nutrients, whereas others will receive more. Either eventuality is likely to alter the local ecosystem. Coral reefs in the Archipelagic Deep Basins province are generally likely to be more strongly affected, although reefs close to localised upwelling, and high islands, should continue to receive adequate nutrients.

5.7 Projected changes: coral reefs under low versus high CO_2 emissions

The primary intention of this chapter is to establish credible pictures of what coral reefs will look like under two distinct CO_2 emissions scenarios for this coming century. In this respect, we extend the analyses of atmospheric climate and the Pacific Ocean undertaken in Chapters 2 and 3, based on the extensive modelling for the Special Report on Emissions Scenarios and the IPCC process[10,120,121] (Chapter 1), to explore the effects of a low emissions (B1) and a high emissions (A2) scenario on coral reefs in 2035 and 2100.

As described above, under these two globally referenced background scenarios, SST in the tropical Pacific is expected to increase within the range of 0.5–1.0°C, atmospheric CO_2 to build up to around 430–450 ppm, and sea level to rise by 6–10 cm by 2035. Given the short amount of time to this point (~ 25 years), changes to the atmosphere and tropical Pacific Ocean under the B1 and A2 scenarios are expected to be largely indistinguishable in 2035, diverging only later this century (Chapters 2 and 3). By 2100 under the B1 and A2 emissions scenarios, SST is expected to be 1.0–1.5°C and 2.5–3.0°C warmer, atmospheric CO_2 is projected to reach 500–600 ppm and 750–800 ppm, and sea level to rise by at least 18–38 cm and 23–51 cm (but see Section 5.6.5), respectively, relative to 1980–1999 (Chapters 2 and 3). In addition, changes to rainfall, ocean circulation and upwelling, and the possibility of more intense cyclones, are projected in 2035 and 2100. The relative vulnerability of coral reefs to each of these variables (Section 5.6) is summarised in **Table 5.2**.

Taken together, these projections define the exposure of coral reefs to the two scenarios for the remainder of the 21st century. By combining exposure with the sensitivity and adaptive capacity of corals described above, it is possible to provide credible projections of how coral reefs are likely to be altered by 2035 and 2100.

Table 5.2 Summary of the vulnerability of coral reefs to the key variables associated with increases in carbon dioxide and other greenhouse gases.

Sea surface temperature	Solar radiation	Ocean acidification	Cyclones and floods	Sea-level rise*	Ocean circulation
Very high	Low	Very high	Moderate	Low-moderate	Moderate

* There is significant uncertainty regarding the rate at which polar ice will melt (Section 5.6.5), which will be an important determinant of the vulnerability of coral reefs to sea-level rise.

5.7.1 The next two to three decades: coral reefs in 2035 (B1 and A2)

Conditions under the B1 and A2 scenarios are expected to be similar in 2035 (Chapters 2 and 3), therefore they are discussed together here. The projected steady increase in SST is expected to cause coral bleaching to occur twice as frequently as it does today (**Figure 5.10**). Several episodes of mass coral bleaching are likely to have occurred by 2035, equalling or exceeding those of 1998 when coral reefs all over the world bleached and 16% of the world's corals died within 9 months[24,68]. Coral reefs in the Pacific were affected variably by the 1998 bleaching event, with the southwest and northeast parts of the region experiencing minimal bleaching, and the southeast and northwest Pacific experiencing moderate to severe bleaching[68].

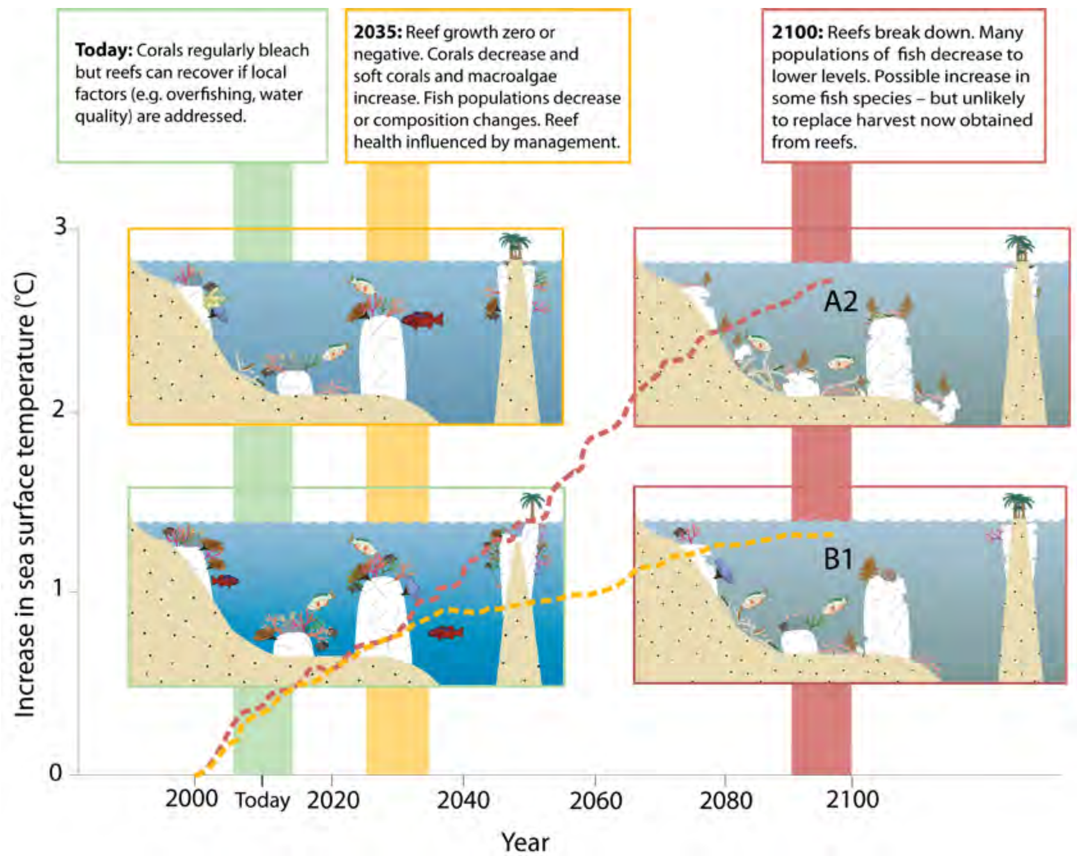


Figure 5.10 The future of coral reefs under B1 and A2 emissions scenarios. Note that the B1 and A2 trajectories are largely indistinguishable by 2035 but diverge after 2050. Under the B1 scenario 2100, coral populations are projected to decrease and reefs are expected to be dominated by non reef-building species. Under the A2 scenario in 2100, sea surface temperatures and ocean acidity, as well as other factors such as turbidity and possibly cyclone intensity, are expected to increase. This is likely to lead to the complete loss of reef-building corals from reefs. Yellow and red vertical columns correspond to the range of years used to model the B1 and A2 emissions scenarios.

The steady downward trajectory of coral cover (1–2% lost per year)[52] is likely to continue until 2035 (Figures 5.10 and 5.11), with loss of another 25–65% of coral cover. Given the increased levels of stress, this annual projected rate of loss is conservative and is expected to be higher than that reported earlier[52]. Average coral cover throughout the tropical Pacific is projected to be around 15–30% in 2035 (**Table 5.3**), compared with 20–40% in 2007[52], and dominated increasingly by more robust species, such as *Porites* and *Favia*, and less by branching species, such as *Acropora* and *Stylophora* (**Figure 5.12**). Some coral reefs are likely to have been significantly affected by more frequent bleaching events, as described above, with coral communities disappearing completely from these reef systems. At this time, management efforts aimed at reducing local threats, such as overfishing and pollution (Section 5.9), will have an important effect on the health of coral reefs, given that reef-building corals are likely to be struggling to remain as significant members of the ecosystem. In particular, effective management interventions should lead to a slower decline in coral cover (**Figure 5.11**).

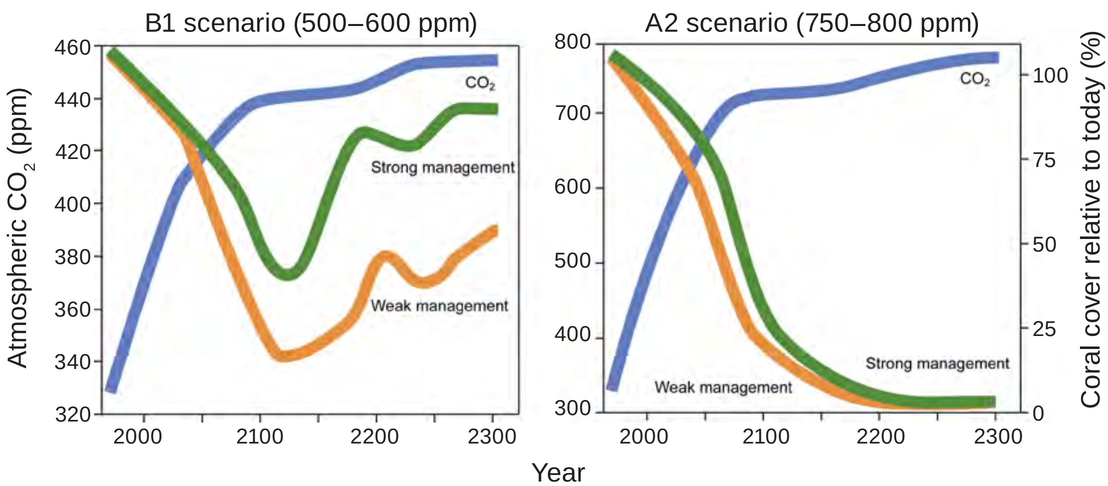


Figure 5.11 Indicative potential changes in carbon dioxide (CO_2) and coral cover over the next three centuries in a world which strongly reduces greenhouse emissions under the B1 scenario (left panel) or does not and follows the A2 scenario (right panel). The orange lines indicate likely changes to percentage coral cover for reefs if they are managed poorly. Green lines depict how coral cover is expected to change where strong policies and actions to manage and reduce local threats are implemented.

Competition between reef-building corals and non-calcareous macroalgae is expected to have intensified by 2035 as coral cover, growth and calcification continue to decrease[53,75]. As a result, macroalgal populations are likely to increase (**Table 5.3**). The projected atmospheric concentrations of CO_2 of 430–450 ppm in 2035 are expected to increase the acidity of the ocean further. Carbonate ion concentrations in large sections of the tropical Pacific Ocean are expected to decrease rapidly towards the levels where growth of many coral species cannot be sustained. The calcification of long-lived *Porites* colonies in 2035 is likely to be 50% less than that seen in the early 1990s. Many reef systems in the Pacific (especially those at higher latitudes and behind the reef crest or in lagoons) are expected to experience physical and biological erosion that exceeds calcification.

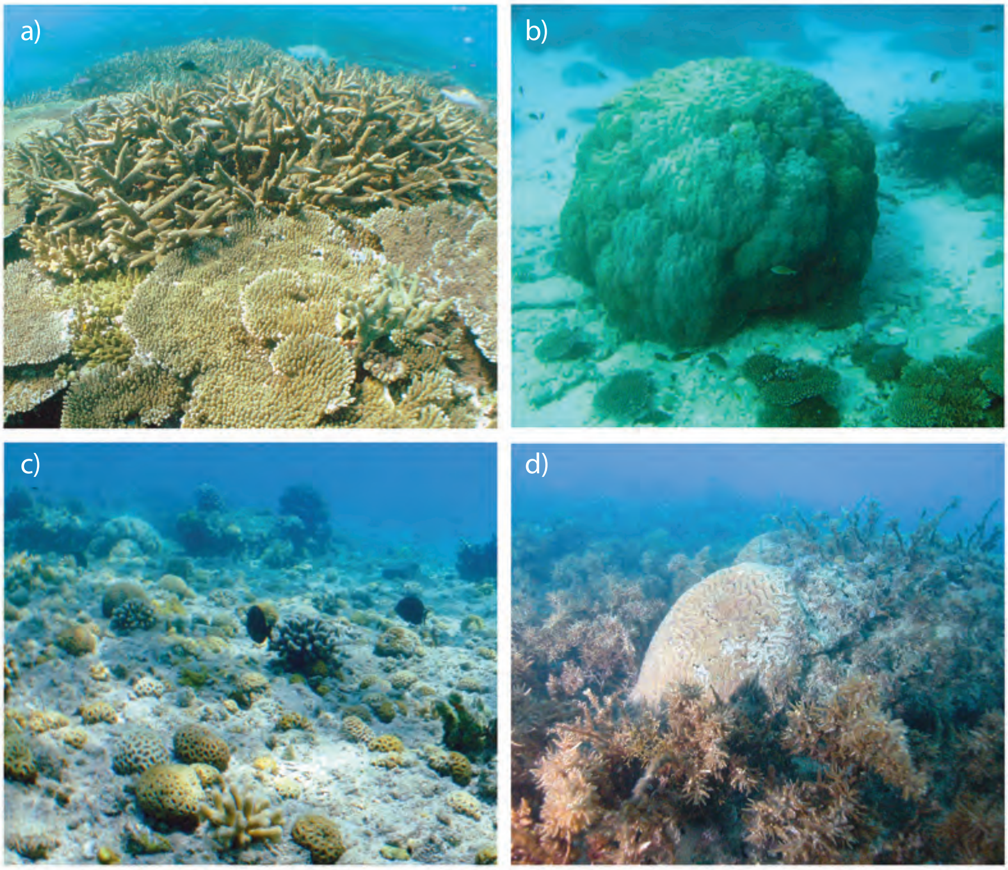


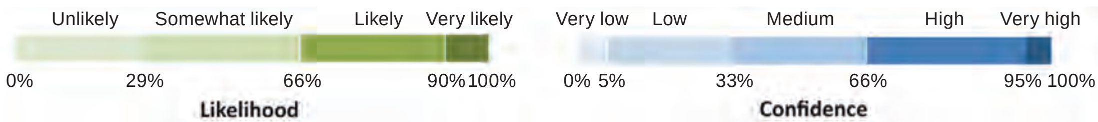
Figure 5.12 Slight differences exist between different coral species with respect to their sensitivity to climate change, particularly increased sea surface temperature (SST). Branching corals, like those shown in (a) are more sensitive (by 1–2°C) than encrusting and massive corals such as the colony shown in (b). These differences in sensitivity are very likely to lead to the reduced presence of branching corals within coral communities depicted in (c). There is less certainty when it comes to the response of other organisms such as macroalgae, which increase in prominence on reefs that have lost reef-building corals, as illustrated in (d). Whether fleshy macroalgae will be able to tolerate future SST of 2.5–3.0°C is not known (photos: Ove Hoegh-Goldberg).

The reduced structural complexity of coral reefs is projected to begin to affect the demersal fish associated with coral reefs. The species composition of this fish assemblage is expected to have greater proportions and abundances of herbivores, such as surgeonfish (Acanthuridae), rabbitfish (Siganidae) and parrotfish (Scaridae), and fewer coral-dependent species, and predatory species (Lethrinidae, Lutjanidae, Serranidae), now prized for their food and income value[41,66,122] (Chapter 9).

The largest impacts on coral reefs by 2035 are expected to occur along coastlines where land use has removed forests and destabilised catchments, causing rivers to transport increasing amounts of sediment and nutrients onto struggling coral reef habitats (Chapter 7). The problems that coral reefs face from declining water quality will be exacerbated where mangroves have been removed or damaged, because of the reduced capacity to retain sediments (Chapter 6). In such nearshore coastal ecosystems, the amount of macroalgae is expected to increase (**Table 5.3**), potentially out-competing corals due to the faster growth rates of macroalgae under higher temperatures and nutrient levels. The greater frequency of more intense droughts and floods and the possibility of intensified tropical cyclones (Chapter 2) are projected to amplify these problems in some parts of the region.

Table 5.3 Estimated projected changes in the percentage cover of live coral and macroalgae on reefs in 2035 and 2100 for the B1 and A2 scenarios under poor and strong management, relative to 2010. The expected remaining cover (%) of coral and macroalgae (including fleshy algae and algal turfs) is also shown. Likelihood and confidence associated with the projections are based mainly on the combined understanding of the expected responses of coral and macroalgae.

Year	Scenario	Management	Coral cover		Macroalgal cover	
			%	% decrease	%	% increase
2035	B1/A2	Strong	15–30	25–65	40	130
		Poor	15	65	40–60	130–200
2100	B1	Strong	10–20	50–75	50	> 150
		Poor	< 5	> 85	80	> 250
	A2	Strong	< 2	> 90	> 95	> 300
		Poor	< 2	> 90	> 95	> 300



In summary, reef-building corals will decrease ~ 25–65% by 2035 (**Table 5.3**), reducing the structural complexity of coral reefs and their ability to provide habitat for fish and invertebrates, many of which are currently of great importance to the people of the tropical Pacific for food security and livelihoods (Chapter 9). The projected loss of reef-building corals is likely to occur given that the current annual reduction in coral cover of 1–2%[52] will result in such losses within 20–30 years.

Management actions are likely to reduce the magnitude of the loss, although the benefits of management are not expected to differ between the B1 and A2 scenarios in 2035. Coral mortality is usually followed by algal colonisation, so that coral reefs are also likely to experience a 130–200% increase in benthic algal cover, including algal turfs, and non-calcareous macroalgae (**Table 5.3**), depending on the strength of management. An analogy for this type of change is provided by coral reefs in the Caribbean, which declined in a similar way[50], resulting in < 10% coral cover[123]. In 2035, reef-building corals are likely to have 50% lower rates of calcification than before 1990, with large sections of coral reef frameworks starting to crumble and break down. However, the deterioration of reef frameworks is only expected to start to become a problem in 2035 and coral reefs should still provide substantial benefits at this point, e.g. coastal barriers to ocean waves, and protection for coastal infrastructure and human dwellings. This particular role of coral reefs will grow in importance as sea level rises, and if coastal areas experience more intense tropical cyclones.

5.7.2 Coral reefs in 2100 (B1)

By the middle of this century, the trajectories of the B1 and A2 scenarios diverge (**Figure 5.10**). In the B1 world, growing awareness of the serious implications of climate change compels governments to pursue strong international agreements for limiting greenhouse gas emissions as formulated under the United Nations Framework Convention on Climate Change (UNFCCC). Once adopted, the results of these international agreements lead to a major revolution in how energy is generated, driven by an energised business sector that responds quickly to new emerging markets leading to rapidly declining greenhouse gas emissions in the decades that follow.

The developed nations rapidly convert to renewable energy sources, such as wind, wave, geothermal and solar thermal power, with expansion of nuclear power options via next-generation technologies. Similar transitions and innovation occur in the emerging economic giants, China and India. Atmospheric CO_2, and hence global temperature, continues to rise over much of the century, albeit at much lower rates than under A2. Perhaps more significantly, CO_2 and other greenhouse gases begin to stabilise in the atmosphere towards the end of the century (in contrast to the A2 scenario under which they do not; **Figure 5.11**). The slowing rate of rise in temperature and atmospheric CO_2 concentrations begins to reduce the rate at which coral reefs decline.

Nevertheless, the projected increase in SST in the tropical Pacific of 1.0–1.5°C relative to 1980–1999 is expected to create conditions in which mass coral bleaching occurs every 1–2 years. Many branching corals and other sensitive reef fauna are likely to disappear from coral reefs, which are instead represented by communities of massive coral species, such as *Porites*, and encrusting species, such as *Favia* and *Favites* (**Figure 5.12**). Under strong management of local stressors, total coral populations are expected to continue to decline and are likely to fall to 10–20% cover across the region (i.e. 25–50% of average coral cover today) (**Table 5.3**). At the same time, the growth of algae (mainly algal turfs) is likely to increase by > 150%. If the management of local stressors is poor, coral cover is likely to fall to lower levels (< 5%) and macroalgal cover is expected to increase by > 250% to ~ 80% cover (**Table 5.3**).

Reef calcification is expected to be 50% of the rate before 1980, and physical and biological erosion is likely to dominate the carbonate balance of coral reefs. The structural complexity of reefs is also likely to have decreased, removing much of the habitat for at least 50% of fish species previously associated with them. Herbivore populations may also be reduced due to the ecological requirements of these fish and invertebrate species for structurally complex reefs (Chapter 9), and their dependency on other coastal habitats such as mangroves and seagrasses (Chapter 6). Damage to coastal ecosystems may also increase due to the possibility of an increase in the number of category 5 cyclones in non-equatorial regions, and greater and more fluctuating rainfall close to the equator, which is likely to be 10–20% higher than in 1980–1999 (Chapter 2).

At the end of this century, under the B1 scenario, coral reefs in the tropical Pacific are likely to have reduced coral cover (**Table 5.3**) and to be less diverse. Management of these reef systems will have a significant effect and strong intervention should lead to healthier reefs under the B1 scenario (**Figure 5.11**). Calcification rates are not expected to keep pace with physical and biological erosion, however, leading to the collapse of many reef frameworks and the loss of habitat. As a result, the production of coastal fisheries is expected to decrease by 10–20% (Chapter 9). These changes, together with the expected rise in sea level, will mean that the coastal protection offered by coral reefs is no longer provided. This could have significant consequences for coastal urban areas and infrastructure, especially in those PICTs comprised of low-lying atolls[124].

5.7.3 Coral reefs in 2100 (A2)

Under the A2 emissions scenario , pressure from special interest groups and a lack of effective government leadership result in weak international agreements to address climate change. Politicians preside over minimal responses, with the outcome that CO_2 emissions are reduced by only 30% of 1990 levels by 2050. It is important to note, however, that the A2 scenario results in lower emissions of CO_2 than the present global trajectory, which is adding 2 ppm CO_2 to the atmosphere each year (Chapter 2). Even under the A2 scenario (here 'worst case'), atmospheric CO_2 is expected to increase to > 700 ppm by 2100, driving ocean pH below 7.7 and carbonate ion concentrations well below the level needed to maintain coral reefs. Sea surface temperatures in the tropical Pacific are projected to rise to 2.5–3.0°C above 1980–1999 levels (Chapters 2 and 3), creating conditions hostile to reef-building corals and other calcifying organisms.

The changes projected under the A2 scenario are expected to cause many coral species to become extinct or extremely rare[125]. Other coastal habitats in many parts of the tropical Pacific may also be affected by sea-level rise and the possibility of increasingly strong cyclones (Chapter 6). Many low-lying atoll nations face increasing threats from storm damage, coastal inundation and the loss of fresh water supplies as coastal aquifers become flooded with sea water[9].

By 2100, coral reefs are likely to be dominated by algal turfs and organisms other than corals (e.g. cyanobacteria) (**Table 5.3**) and the few corals present (< 2% of total cover) are likely to be very robust extremophiles. Net reef accretion is projected to be non-existent and reef structures are expected to break down under physical and biological erosion (**Figure 5.10**). Demersal fish populations are also likely to be fundamentally different, with their productivity projected to be 20–50% lower than in 2010 (Chapter 9). No amount of management action to reduce local threats has any effect on reef health (**Figure 5.11**, **Table 5.3**).

Photo: Katharina Fabricius

Coral reef damaged by a severe storm

5.7.4 Beyond 2100: reef recovery versus complete collapse

In exploring the consequences for coral reefs of choosing a B1 versus A2 future path, it becomes important to consider what lies beyond 2100. While seemingly distant, the success or failure of efforts to stabilise greenhouse gas concentrations in the 21st century will have serious ramifications for the future of reefs, and those who depend on them, beyond 2100 (**Figure 5.11**).

Strong action on greenhouse gas emissions, and vigorous attempts to reduce the effects of local threats such as declining water quality from pollution, overfishing, destructive fishing practices and mining, could help coral reefs in the B1 world to redistribute and regenerate around the Pacific as conditions stabilise. Over time, populations of corals adapted to warm conditions at the equator are expected to expand slightly towards higher latitudes. These coral populations will struggle, however, to maintain structurally complex carbonate reef systems because of the low concentrations of carbonate ions in the oceans of the next century and beyond. Nevertheless, these populations should be able to build coral reefs with a degree of diversity, similar perhaps to those currently found in the eastern Pacific[126]. Although these reefs are expected to have low biodiversity and no net accretion of carbonate structure, they should continue to support substantial fish populations and fisheries.

In contrast, the A2 scenario, with its rapid and continuing changes to SST, ocean pH, carbonate ions and sea level, is expected to result in environmental conditions that continue to outpace ecological processes for centuries to come. This would lead to 'chaotic', low-productivity coral reefs, with little value for the people of the Pacific.

5.8 Uncertainty, gaps in knowledge and future research

While there is little doubt that climate change represents a serious threat to coral reefs, and the people who depend on them, there are a number of important gaps in our current understanding of how coral reefs will change, and how we might respond. These important questions and gaps are outlined below.

- How will the climate change at the scale of individual PICTs and their coastlines? Global models for how climate change is projected to affect the tropical Pacific must be 'downscaled' to provide information which managers and policy makers in PICTs can use to respond to the regional and local problems.
- How is warming and acidification of the tropical Pacific Ocean affecting the early life history stages of corals and other key reef-building organisms? What are the knock-on effects of these types of influences on the fundamental biology of coral reef organisms?
- What important synergies might occur between the projected changes to SST and ocean acidity, and other factors such as the possibility of more intense cyclones?
- Is the restoration and remediation of coral reefs damaged by climate change feasible, either biologically or economically?
- What are the most effective management strategies for reefs that have suffered short- and long-term coral bleaching episodes? For example, should a fishing closure be put in place until a reef has recovered from a severe bleaching event?
- Are current monitoring protocols adapted to climate change? What needs to be done to monitor reefs and their communities to separate local versus global effects?
- What are the likely consequences of very rapid rates of sea-level rise (of up to 2 m by 2100) for tropical Pacific coral reefs?
- How should management strategies change as the ecological community composition of coral reefs varies from, for example, branching corals to more massive corals and macroalgal-dominated seascapes?

Forming international science partnerships, for example, with the Global Environmental Facility Coral Reef Targeted Research Programme, Grand Observatoire du Pacifique Sud, Coral Reef Triangle Initiative, Micronesia Challenge, and Pacific Oceans Solutions, will assist the Pacific communities to fill these knowledge gaps. Such partnerships extend the often limited resources of PICTs, and should help to ensure that they understand and address the problems posed by declining health of coral reefs.

Photo: Gary Bell

Coral bleaching

To empower PICTs to respond effectively to the challenges facing coral reefs due to projected climate change, the following four major research activities need to be implemented.

- Support the Pacific Climate Change Science Programme initiatives to increase understanding of changes to surface climate in the region and the tropical Pacific Ocean[ii].
- Improve our understanding of how climate change at regional and local scales is likely to affect critical features of coral reefs. In particular, we need more information on the expected effects on the three-dimensional architecture of coral reefs that is so important for fisheries and many other species, and what can be done to avoid the worst impacts. Real-time information on how environmental stressors, such as SST, vary spatially and temporally will be critical to understanding where vulnerabilities within reef systems are likely to arise, and how to design appropriate management responses. The satellite products provided by the National Oceanic and Atmospheric Administration of the USA (NOAA) through its Coral Reef Watch programme[127] are valuable tools in this respect. The products could be improved further, however, by (1) providing finer-scale measurements (< 1 km) on the scale needed to manage individual reefs; and (2) integrating data on light intensity, pH and turbidity with SST, to assess the risks of damaging synergistic effects that may result from changes in SST, even though thermal stress (degree heating weeks) does not reach threshold levels.

ii This work is now being done for the tropical Pacific by the Australian Bureau of Meteorology, CSIRO and partners, under the Pacific Climate Change Science Programme; see www.cawcr.gov.au/projects/PCCSP

- Assess the interaction between the effects of local stressors to coral reefs and global warming and increased emissions of CO_2, and explore possible opportunities to improve the management of coral reefs under a changing climate.
- Map the socio-economic vulnerability of Pacific people to the projected changes in coral reefs, and explore how governments can respond today to avoid the losses of ecological services and their effects on food security and livelihoods.

This last priority is discussed further in Chapters 12 and 13. Actions that are taken today will generally reduce the potential socio-economic effects and be less expensive than waiting to tackle the problems in the future.

5.9 Management implications and recommendations

The difference between the two scenarios discussed here is essentially a world of challenging yet largely manageable impacts (B1) versus a world that will have to address a series of calamitous and unmanageable outcomes caused by the rapidly changing climate (A2). To avoid an A2 world, the international community must commit to immediate and deep reductions in CO_2 emissions. The most credible models recommend that the emission of atmospheric CO_2 and other greenhouse gases must be reduced by at least 90% compared with 1990 levels by 2050[105,128]. Not to act on emissions is to invite a catastrophic future and to fail future generations and societies.

Even if the most decisive action is taken to reduce emission of greenhouse gases, the projected effects of climate change on coral reefs represents a major challenge for PICTs. At a minimum, these valuable habitats are expected to be altered by the consequences of the emissions that have already occurred (as outlined in Chapters 2 and 3), although it is likely to take time for the effects of these emissions to eventuate fully.

In addition to mitigation of the emissions of CO_2 and other greenhouse gases, the onus is on governments to manage coral reefs in a way that will maximise their natural adaptive capacity or ability to cope with future changes (resilience) (**Figure 5.13**). Key recommendations for local management measures are summarised below.

- Strategies to limit the flow of nutrients and sediments from rivers and coastal catchments on to coral reefs must be implemented. These will involve restoring and protecting riparian and coastal vegetation cover, maintaining mangroves and seagrass meadows, and implementing a broad range of integrated coastal zone management measures, as outlined in Chapters 6 and 7. Such interventions will give corals and coral reef organisms threatened by climate change the best chances of resisting, and building tolerance to, thermal stress and rapid sea-level rise. In relation to sea-level rise, the future potential for growth of corals on existing intertidal fringing reefs on high islands will depend on minimising runoff. This will require careful planning given the projected increase in rainfall in equatorial regions (Chapter 2).

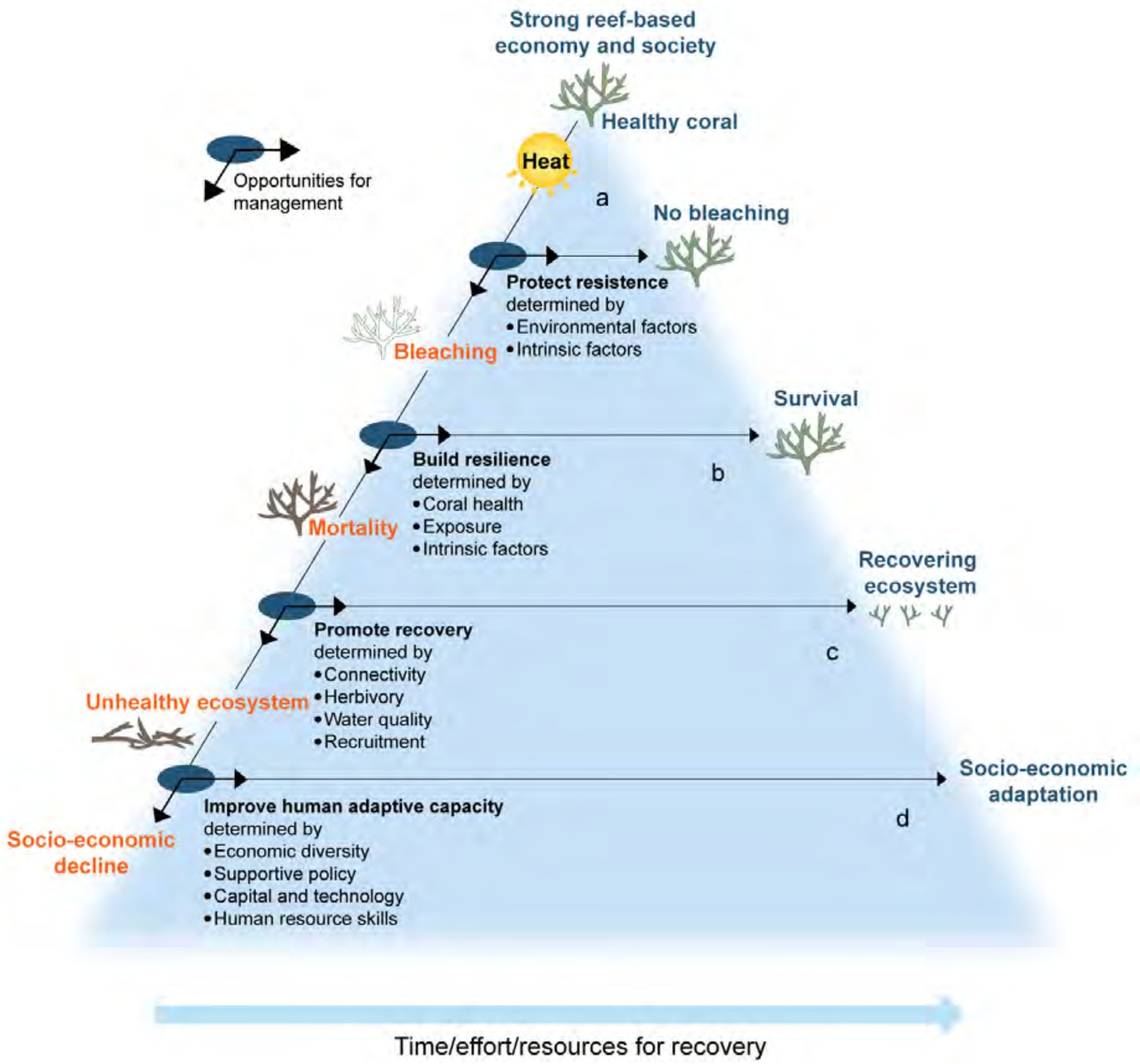


Figure 5.13 Opportunities for management interventions to improve outcomes under increased episodes of mass coral bleaching. Pyramid shows four strategies for responding to climate-driven increases in thermal stress and mass coral bleaching on a typical reef (a) increasing the resistance of reef-building corals to thermal stress will reduce impacts like coral bleaching, which involves minimising local stresses that might weaken the physiological resistance of corals to thermal stress; (b) building the tolerance of corals to regular bleaching will minimise mortality; (c) once mortality has occurred, promoting the recovery of reefs from episodes of mass coral bleaching will be important, for example, protecting herbivores on bleached reefs can improve recovery by grazing algae[130]; and (d) improving the adaptive capacity of dependent human populations to withstand the loss of key coastal resources is an important strategic response (Chapter 13) (source: Marshall and Schuttenberg 2006)[129].

- Measures to assist corals to resist bleaching, and to recover from bleaching events when their thermal tolerances are exceeded[124], must be modified to suit PICTs and applied across the region. These measures are designed to address the hierarchy of effects of thermal stress on corals (**Figure 5.13**). At one end of the continuum, healthy coral reefs support reef-based economies and societies, and at the other, a damaged and unhealthy ecosystem leads to serious socio-economic consequences. At each point in this hierarchy, different strategies are needed. For example, for a relatively healthy reef, reducing the effect of local stressors (environmental factors) should help increase the resistance of corals to bleaching. Also, where bleaching does occur, considerable evidence has shown that populations of corals will recover faster if their ecological resilience is protected and enhanced[57]. Bleached coral reefs, on which grazing fish populations have been maintained to control algal growth, illustrate this point well. Such reefs recover three times as fast as reefs where grazing fish populations have been removed[130].

- Activities that damage the three-dimensional structure of coral reefs need to be prevented, especially because reef frameworks provide habitats for reef-dwelling species, including many fish and invertebrates used for subsistence and livelihoods (Chapter 9). Reef barriers also play essential roles in protecting coastal ecosystems such as mangroves and seagrass meadows, which are often nursery habitats for the juvenile stages of coastal fish species (Chapter 6). Measures that will help preserve reef frameworks in the face of climate change are the elimination of destructive fishing activities (particularly dynamite fishing), mining of coral rock, and damage from boating and tourist operations.

Assisting human populations to adapt to the loss of coral reefs and their associated resources will also be essential. However, the success of management interventions designed to enable coastal communities to adapt to the degradation and loss of coral reefs will depend largely on understanding that governance in many PICTs is weak. Management measures designed for the Great Barrier Reef, for example, will not be appropriate for many PICTs, because they rely heavily on reefs for food security and lack the resources to implement and monitor compliance with such interventions and regulations. A different approach is needed – one that (1) recognises the important role of subsistence and commercial fishing, and livelihoods based on the other attributes of reefs, for the coastal people of the Pacific, and (2) provides incentives for coastal communities to value and nurture coral reefs using simple management measures[44].

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