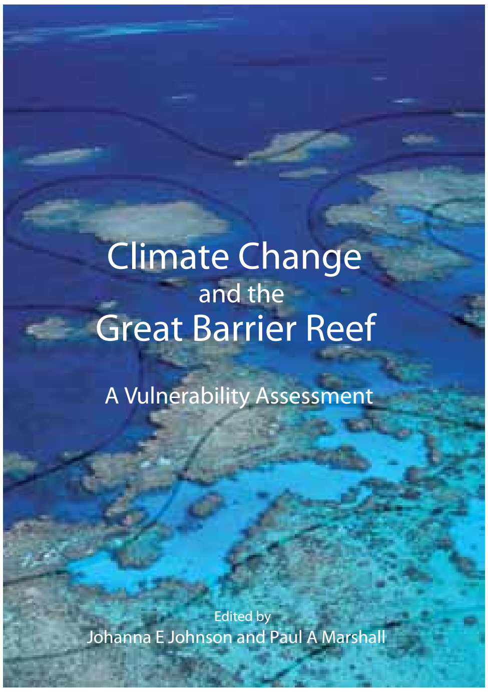

Climate Change and the Great Barrier Reef

A Vulnerability Assessment

Edited by Johanna E Johnson and Paul A Marshall

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Available from: Great Barrier Reef Marine Park Authority
2–68 Flinders St, PO Box 1379, Townsville, Qld 4810, Australia
Tel: +61 7 4750 0700, Fax: +61 7 4772 6093
Email: info@gbrmpa.gov.au

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Part IV: Enabling management

Chapter 24

The Great Barrier Reef and climate change: vulnerability and management implications

Paul A Marshall and Johanna E Johnson

Image courtesy of Triggerfish Images

This book provides an authoritative assessment of climate change vulnerability for the species and habitats that make up the Great Barrier Reef (GBR). The picture that emerges from the combined knowledge of 86 experts is that the GBR is exposed to a range of stressors associated with climate change, and that many components of the GBR (which includes both ecological and human dimensions) are highly sensitive to these stressors. While the GBR is likely to be more resilient to climate change than most tropical marine ecosystems around the world, it is far from immune to this pervasive threat. In fact, signs of vulnerability to climate change are already being observed in critical parts of the GBR ecosystem, such as corals and seabirds. In addition to presenting a synthesis of current and emerging knowledge, the experts who contributed to this assessment provided recommendations for ways to reduce the impacts of climate change on the GBR. These insights provide the foundations on which tropical marine ecosystem managers can build an informed and effective response to climate change.

In this chapter, we begin with a synopsis of previous chapters, covering the latest knowledge on exposure, sensitivity and vulnerability of the GBR to climate change. Building on this summary, we synthesise ideas about potential management responses suggested by the contributing experts. The findings of this vulnerability assessment provide a rigorous and comprehensive basis for management planning and policy. The information in this final chapter is provided as a summary of the opinions of scientific experts.

24.1 Vulnerability of the Great Barrier Reef to climate change

The combination of sensitivity and exposure to climate change render the GBR ecosystem highly vulnerable to climate change. While the components and processes that comprise the ecosystem vary in their vulnerability, the implications of climate change are far-reaching and, in many cases, severe. Overall, the GBR ecosystem has features that will afford it some protection from climate change compared with tropical marine reef ecosystems. These features include its immense size, its location adjacent to a relatively sparsely populated and developed country, and its protection under a management regime that is recognised as the best in the world[20]. However, coral reefs are one of the most vulnerable of all of the earth's ecosystems to climate change[10], and the GBR will continue to be affected. Even under the most optimistic climate change scenarios, the GBR is destined for significant change over this century; under pessimistic scenarios, catastrophic impacts are possible[2]. In this section, we provide an overview of the exposure of the GBR to climate factors, including a summary of predicted changes to the GBR climate, followed by a review of the reasons for the sensitivity of the GBR to climate change. We then provide a synopsis of current and emerging knowledge about the vulnerability of GBR species groups and habitats to climate change.

24.1.1 Exposure of the Great Barrier Reef

Climate change is unlike any disturbance experienced by contemporary coral reefs: it has the potential to simultaneously and severely affect tropical marine ecosystems spanning hundreds and thousands of kilometres. Further, the spatial extent of exposure applies to nearly every climate variable, many of which are projected to change rapidly over the coming century. Changes associated with climate change that have implications for the GBR include increasing air and sea temperatures, ocean acidification, nutrient enrichment (via changes in rainfall regimes), altered light levels, more extreme weather events, changes to ocean circulation and sea level rise.

This vulnerability assessment confirms that increasing sea temperature is the single biggest risk factor for the GBR over the short- to mid-term (years to decades). Sea temperature increases are the major cause of the predicted decline in coral communities over the current century, with flow-on effects through the entire ecosystem. Warming of the GBR will also directly affect other components of the ecosystem, and will be a major source of stress for many marine plants and animals.

Over longer time scales (decades to centuries), ocean acidification is likely to surpass temperature as the environmental variable of most significance to the sustainability of the GBR ecosystem. Ocean acidification is expected to have major impacts on the ability of corals, calcifying algae and some species of plankton, crustaceans and molluscs to form their skeletons and shells. This threatens the persistence of the carbonate structures that define coral reef habitats.

Changes in patterns of ocean circulation are likely to have far-reaching effects, particularly on key processes such as connectivity and productivity. Potential impacts on plankton species are likely to be partly offset by the high functional redundancy in plankton communities, but potential effects on the pelagic environment – especially on the location and extent of primary productivity – are cause for concern.

In contrast, current projections indicate that sea level rise is likely to be a relatively minor issue for most reef species and processes in the short- to mid-term. However, sea level rise will become a major source of vulnerability for several important habitats, including coastal and estuarine environments such as mangroves and wetlands, islands and cays (as well as the species that depend on these habitats) should these projections be revised upwards in light of recent concerns about accelerated melting of major ice sheets.

24.1.2 The changing climate of the Great Barrier Reef

Global climate projections have been used in conjunction with regional observations of climate to develop regional (GBR) projections of air temperature, sea temperature and sea level rise that have a high level of confidence. Projections of ocean acidification, in contrast, are based on global models that have limited resolution at the regional scale. Projections for other climate variables, such as ocean circulation, rainfall, storms and tropical cyclones, and El Niño-Southern Oscillation (ENSO) events also have low confidence for regional applications. Major modelling exercises are underway to refine regional climate projections. These programs are likely to significantly increase the resolution and confidence of climate models, at least for some variables. This section summarises current knowledge about the projected changes to air temperature, sea temperature, sea level, ocean chemistry, ENSO and weather events for the GBR region over this century.

Air temperature

Coastal air temperatures in the GBR region have already warmed and are projected to increase by 1.4 to 5ºC (above 1990 temperatures) by 2070[19]. This is significant for habitats exposed to air, such as mangroves, intertidal seagrass and other coastal habitats, as well as islands and cays. Many of the species in these habitats are also sensitive to changes in air temperature, particularly extremes of temperature (eg marine turtles and seabirds).

Sea temperature

Regional GBR sea temperatures have increased by 0.4°C since 1850 and are projected to increase by a further 1 to 3°C above present temperatures by 2100 (Lough chapter 2). Increases have been greater in the central and southern GBR (0.7°C since 1850) and this pattern is likely to continue into the future. An increase in sea temperature is likely to be the most critical of all changes to the region's climate, having implications for most marine species. Species groups from corals and plankton to fish and seabirds are sensitive to these changes (chapters 5 to 16).

Sea level and ocean chemistry

Sea level has already risen and by 2020 is projected to increase by 38 to 68 cm (relative to the 1961 to 1990 baseline). Ocean acidity is projected to increase by 0.4 to 0.5 pH units over the same timeframe (Lough chapter 2). Species and habitats in the intertidal zone are particularly vulnerable to sea level rise, including seagrass, mangroves and associated wetlands, coasts, estuaries and islands and marine reptiles (Waycott et al. chapter 8, Lovelock and Ellison chapter 9, Hamann et al. chapter 15, Sheaves et al. chapter 19 and Turner and Batianoff chapter 20).

ENSO and weather events

There is less certainty about changes to ENSO and weather events such as storms and rainfall. However, while the extent of change is difficult to predict, in general the direction of change can be predicted with moderate confidence. Tropical cyclones are projected to become more severe, with a 5 to 12 percent increase in wind speed projected. Variability of rainfall and river flow is expected to increase, resulting in more intense droughts and rainfall events. ENSO will continue to be a source of high inter-annual variability (Lough chapter 2). Changes to ENSO and weather events, although uncertain, will have implications for many parts of the GBR ecosystem.

24.1.3 Sensitivity of the Great Barrier Reef

The GBR occurs in a tropical ocean realm where key environmental variables, such as sea temperature, generally fluctuate relatively little over seasonal or diurnal time frames. Typically, the range of sea temperature experienced by tropical marine organisms over the course of a year is substantially less than that experienced by terrestrial organisms in a single day. Further, the huge buffering capacity of the oceans has ensured a highly stable chemical environment for the GBR over time scales of centuries and millennia. As a result, many tropical marine organisms have evolved narrow environmental tolerances, rendering them sensitive to apparently small changes in environmental conditions. This sensitivity has resulted in tropical marine habitats such as coral reefs being extremely vulnerable to climate change relative to most other habitats.

Climate change is driving shifts in environmental conditions that are already beginning to exceed the narrow tolerances of many GBR species and affect key processes. However, there is one feature that distinguishes the GBR ecosystem from most other coral reef ecosystems on the planet: its immense size. Covering 344,400 km^2, the GBR Marine Park is immensely complex and heterogeneous in both physical and biological terms. The geographical extent and diversity of habitats act, to some extent, as a safeguard against ecosystem-wide catastrophe. Compared to smaller coral reef ecosystems, the probability of the entire GBR being destroyed by any single disturbance is low. However, while the scale of the GBR acts to reduce sensitivity at the landscape scale, local and regional sensitivity remains high for many species and habitats.

24.1.4 Vulnerability of species groups

A significant source of the vulnerability of the GBR is the extensive connectivity within the marine ecosystem. The linkages and inter-dependencies among organisms, and between organisms and processes, mean that impacts on one component of the ecosystem are likely to have consequences for other components. This connectivity is also an important factor in the resilience of the GBR. This assessment has extended our knowledge of the vulnerability of all parts of the ecosystem, from marine microbes and plankton to fishes and seabirds and charismatic mega fauna. While many species groups have intrinsic sensitivities to climate change, there are also groups that will experience indirect effects. These indirect effects result from the linkages and inter-dependencies among organisms, and between organisms and processes. This extensive connectivity, which characterises marine ecosystems, means that impacts on one component of the ecosystem are likely to have flow-on effects for other components. This section summarises the key vulnerabilities – both direct and indirect – identified for the main species groups in the GBR.

Marine microbes

Marine microbes are a fundamental part of the GBR ecosystem responsible for nutrient cycling (microbial loop), facilitating benthic larval settlement (eg of coral planulae) and for forming partnerships as part of critical symbiotic relationships. The group also includes pathogenic species responsible for disease in many reef organisms such as hard and soft corals, sponges and some echinoderms. Increasing sea temperature, ocean acidification and nutrient enrichment resulting from changes to rainfall patterns are the climate variables that will pose the greatest threat to marine microbes. Short generation times and functional redundancy mean that, functionally, marine microbes are only moderately vulnerable to climate change impacts, as community composition can shift rapidly in response to changing conditions. However, specialised communities (eg sponge symbionts) and some species (eg thermophiles) are likely to be highly vulnerable to climate change. In contrast, pathogenic microbes are likely to be positively affected by climate change with increased virulence and abundance in warming nutrient rich waters. A change in microbial communities that are important in the microbial loop will have implications for the entire ecosystem, which relies on these communities to alter and liberate bioavailable nutrients that are essential for higher trophic levels. A loss of symbiotic microbes will have serious effects on the benthic organisms that rely on symbioses, with implications for sponges, corals and other benthic invertebrates. An increase in disease incidence will have deleterious impacts on the many benthic organisms that are susceptible to disease, particularly if increased sea temperatures and other climate-related changes have already caused stress. As a fundamental component of the marine ecosystem, changes to marine microbial communities will be critical for most other organisms in the GBR (Webster and Hill chapter 5).

Plankton

Plankton are another group that are fundamentally important to marine ecosystems through their roles as the dominant component of pelagic environments (both in terms of biomass and abundance) and as key primary producers. The group is most vulnerable to changes in ocean circulation – critical for plankton distribution and dispersal – and, to a lesser degree, nutrient enrichment through changes to rainfall patterns and upwelling regimes. Increasing sea temperature, ocean acidification and changes to ultraviolet (UV) light may also affect plankton. Due to the short generation times and functional redundancy of plankton, they are able to rapidly respond to environmental change and therefore functionally are only moderately vulnerable to climate change. However, some species (such as the calcifying pteropod Cavolinia sp.) are highly vulnerable to changes in environmental conditions. Changes to the plankton community will have cascading effects on higher trophic levels and are likely to have consequences for most other organisms in the GBR ecosystem (McKinnon et al. chapter 6).

Macroalgae

Macroalgae in marine ecosystems have a diverse range of roles including primary production, carbon storage, nitrogen fixation, facilitating larval settlement and reef degradation. Macroalgae are one of the few groups in the GBR that are likely to benefit from climate change through increased nutrient and substrate availability. Increasing sea temperature, ocean acidification, nutrient and carbon dioxide (CO_2) enrichment and changes to UV light are the climate changes that will directly affect macroalgae. Turf and upright fleshy macroalgae are unlikely to be negatively impacted by climate change and are likely to benefit through increases in productivity, growth and reproduction. Increases in substrate availability due to increased coral mortality (as a consequence of recurrent bleaching) will promote algal colonisation and increase the area of reef covered by turf and fleshy macroalgae. However, this may cause shifts in competitive balance resulting in shifts in species composition, which would lead to algal assemblages that are markedly different in ecological structure and function. Crustose coralline algae are highly vulnerable to ocean acidification with flow-on negative consequences for coral larval settlement and calcification (reef accretion). Increasing growth and reproduction of turf and fleshy macroalgae will have positive consequences for nutrient cycling. However, competition shifts in benthic habitats will result in reef degradation and algal dominated reefs (Diaz-Pulido et al. chapter 7).

Seagrass

Seagrass are a diverse component of the GBR ecosystem, inhabiting both intertidal and deepwater environments. Seagrass are significant primary producers and provide habitat and food resources, sediment stabilisation and local biochemical and hydrodynamic modification. These roles are particularly important for maintaining coastal habitats and limiting sediment and nutrient delivery to inshore coral reefs. Seagrass are most at risk from changes to UV light, which is important for photosynthesis and growth of all seagrass species, particularly as a result of increased turbidity from floods and sea level rise. Other climate changes that pose a threat to seagrass are increasing sea temperature, storms and changes to ocean circulation. Nutrient enrichment and increasing atmospheric and oceanic CO_2 concentrations will also affect seagrass but are likely to have a positive effect by increasing growth rates. Reductions in UV light and reduced light penetration from pulsed turbidity will affect photosynthetic rates, making seagrass communities moderately vulnerable to climate change. While most species have low vulnerability, *Halophila, Halodule* and *Zostera* are sensitive to reduced light levels associated with increased turbidity. Changes in seagrass communities will have implications for nutrient cycling, availability of critical habitat (eg for juvenile fishes) and food resources (eg for dugong and green turtles), sediment stabilisation and local hydrodynamics (Waycott et al. chapter 8).

Mangroves

Mangroves are important primary producers that play major roles in cycling and storing nutrients, and providing critical nursery habitat for many species (eg larval and juvenile fish). They also provide biofiltration and coastal stabilisation services, and are a major influence on local biochemical and hydrodynamic environments. Due to their location in the intertidal zone, mangroves will be affected by sea level rise, particularly if the rate of rise is greater than the vertical accretion rate of mangrove habitats. Reduced rainfall, increased storms, increasing air and sea temperatures, atmospheric chemistry and changes to ocean circulation will also affect mangroves. Overall, mangroves are considered to have moderate to high vulnerability to climate change, depending on the rate of sea level rise. Loss of mangroves and associated tidal wetlands will have implications for higher trophic levels through changes in nutrient cycling, changes to critical nursery habitat, loss of coastal stabilisation and hydrodynamic modification, and for reef organisms, loss of sediment biofiltration and increased nutrient delivery to inshore reefs (Lovelock and Ellison chapter 9).

Corals

While coral reefs comprise only six percent of the overall area of the GBR Marine Park, corals play a fundamental role in the GBR ecosystem. Corals are the major source of calcium carbonate accretion in the GBR ecosystem, making them indispensable for the building and maintenance of the physical foundations of the entire ecosystem. Shallow reef-building corals are highly sensitive to changes in environmental conditions, in particular increasing sea temperature and ocean acidification. Corals will also be affected by changes to light regimes, more intense storms and flood events and changes to ocean circulation. Due to their sensitivity to environmental variables, corals are highly vulnerable to climate change. The potential for climate change to severely affect corals has already been demonstrated through the two severe mass bleaching events that occurred on the GBR in 1998 and 2002. Loss of corals will have catastrophic consequences for reef structure and for reef habitat that is critical for species of reef fish, benthic invertebrates, marine turtles, sharks and rays. In addition, the potential loss of reef-building corals has implications for the physical structure of the GBR, with serious and lasting impacts for other habitats, as well as for the people and industries that depend on them (Hoegh-Guldberg et al. chapter 10).

Benthic invertebrates

Benthic invertebrates (other than corals) are a diverse group of organisms that play important roles in biofiltration of seawater and suspended matter (eg sponges), nutrient and carbon cycling, bioerosion (eg polychaetes), provision of habitat (eg sponges and gorgonians), bioturbation, reef building (eg molluscs), detrital recycling (eg crustaceans) and predation (eg crustaceans and molluscs). Many benthic invertebrates are also commercially important for fisheries, such as some species of prawns, crabs, molluscs and sea cucumbers. Although a diverse group, benthic invertebrates share a high sensitivity to increasing sea temperature. Particular species also have a moderate sensitivity to changes to ocean circulation, storm and flood events and ocean chemistry. The high diversity of benthic invertebrate phyla, encompassing a wide range of life histories, means that species range from low vulnerability (eg highly mobile species such as some cephalopods and crustaceans) to moderate vulnerability (eg moderately mobile species such as some gastropods) to high vulnerability (eg sessile species such as sponges and giant clams). Loss of species that are highly vulnerable to climate change will have consequences for reef structure (modified bioerosion), nutrient cycling and reducing biofiltration of sediments and nutrients (Hutchings et al. chapter 11).

Fishes

Fishes play a critical role in transferring energy through the ecosystem. They fill discrete functional roles, such as high-level predation and algal grazing, that are critical to maintaining ecosystem function. Some species such as coral trout, red-throat emperor, mackerel and snapper, are commercially important.

Fish are sensitive to increasing sea temperature and changes to ocean circulation, both of which are likely to affect population distribution and larval dispersal. Coastal species are also likely to be affected by sea level rise and flood events. The most significant impact on fish from climate change however, is likely to be from modification of habitats that are critical to their life histories, such as coral reefs, mangroves and seagrass meadows. Fish vary in their vulnerability to climate change depending on the climate variable (eg they are more vulnerable to increasing sea temperature than sea level rise) and the habitat occupied (reef-dependent species are more vulnerable than pelagic species). Reduced fish abundance and diversity will have implications for the food web (both higher and lower trophic levels) and for dependent fisheries (Munday et al. chapter 12).

Sharks and rays

Sharks and rays provide an important functional role as top-level predators within the GBR ecosystem. They are essential for regulating prey species such as fish, molluscs and crustaceans. Many shark species provide substantial social and cultural values, and some are taken in significant numbers by commercial fisheries, either as target species or as bycatch. Sharks and rays will be affected by changes in sea temperature, changes to ocean circulation and freshwater inputs as a result of changing rainfall patterns. The most significant vulnerabilities for this group relate to modification of coastal habitats such as estuaries and mangroves, and disruption of ecological processes that drive productivity and availability of prey through rainfall and oceanographic changes. Of sharks and rays, freshwater and estuarine species are highly vulnerable to climate change impacts and most at risk. Reef species are moderately vulnerable to climate change through the effects of sea temperature and ocean acidification on tropical marine habitats. The implications of this vulnerability will manifest as changes in the food web and at lower trophic levels. Other shark and ray species have low vulnerability to climate change, as they are generalists or mobile. However, this low vulnerability is dependent upon their ability to move and exploit other habitats and resources (Chin and Kyne chapter 13).

Seabirds

Seabirds are highly visible predators in the GBR ecosystem that are defined by the fact that they feed exclusively at sea. They feed on bait fish aggregations in nearshore, offshore and pelagic surface waters and interact with in-water predators by driving bait fish schools deeper. They also provide a dispersal mechanism for mainland and island plants. Seabirds are highly vulnerable to increasing sea temperature and changes to ocean circulation and ENSO. These climate drivers affect the distribution of warm waters and therefore bait fish aggregations. Seabirds rely on these productivity 'hot spots' for survival and breeding success. Sea level rise also poses a risk to seabirds as some important nesting islands and cays are likely to be inundated. Particularly vulnerable groups include pelagic foraging terns, wedge-tailed shearwaters and many species of boobies. Catastrophic breeding failures and population declines are possible with successive warm years, which will have implications for the wider marine food web, particularly lower trophic levels, and plant seed dispersal. It would also represent a loss of a charismatic component of the GBR ecosystem (Congdon et al. chapter 14).

Marine reptiles

Marine reptiles, namely turtles, crocodiles and sea snakes, fulfil various ecological roles (from herbivory to top-level predators). Of all marine reptiles in the GBR, turtles are most at risk from climate change. They are particularly sensitive to increasing air and sea temperature (which will affect hatchling incubation and gender determination) and sea level rise (which may alter the suitability of important nesting beaches). Increased temperatures are likely to have a similar impact on the incubation of estuarine crocodile eggs, but the thresholds are more difficult to determine. Overall, crocodiles and sea snakes are predicted to be only moderately vulnerable to climate change. Likely responses to changed climatic conditions include shifts in the timing of the nesting season and shifts in nesting locations. Changes to the gender ratio of marine reptiles or loss of critical breeding sites – and therefore breeding failure – will have implications in the long-term for populations, and flow-on effects to other trophic levels and the maintenance of cultural traditions of Indigenous Australians (Hamann et al. chapter 15).

Marine mammals

Marine mammals of the GBR are an ecologically diverse group and include one species of dugong, 16 species of dolphin and 15 species of whale that are resident or spend part of their life in the GBR. Whales most often inhabit deep-water habitats or migrate from summer feeding grounds in Antarctica to winter breeding grounds in the GBR. Dugongs perform important community and chemical modifications to seagrass habitats, dolphins are top-level predators and whales contribute to nutrient cycling. All marine mammals provide important social and cultural values. The climate drivers that are most likely to affect marine mammals are changes to ocean circulation, storms, flood events and increasing sea temperature. Due to their migratory and mobile nature, marine mammals have only low to moderate vulnerability to climate change within the GBR context. The most significant impacts of climate change on marine mammals are likely to be through their food resources, either through changes in seagrass meadows or the availability of plankton or fish. The sources of these effects extend beyond the GBR, as some marine mammals that frequent the GBR depend upon food resources from other regions, such as Antarctica. Changes to marine mammal populations in the GBR will have some flow-on effects on lower trophic levels (Lawler et al. chapter 16).

24.1.5 Vulnerability of habitats

The GBR is substantially more than the sum of its parts. The complex inter-dependencies and links between species and their environment create many recognisable habitats with emergent properties that cannot be attributable to any one species or group of organisms. These habitats normally facilitate the processes and qualities that are both necessary for maintenance and renewal, and essential for the survival of species. Understanding the vulnerability of habitats, in addition to the vulnerability of their composite species, is critical to management of natural resources. This section summarises the key vulnerabilities of the main habitats of the GBR ecosystem as assessed in previous chapters.

Coral reefs

Coral reefs are an iconic component of the GBR that, while comprising only six percent of the area of the GBR Marine Park, provide critical habitat and food resources for many species in the ecosystem. The vulnerability of coral reef habitats to climate change is high as the dominant structural components (scleractinian corals) are highly vulnerable to increasing sea temperature and ocean acidification. The increased frequency of coral bleaching that will accompany further increases in sea temperature will cause a decline in coral cover, increases in algal dominance, and shifts to the composition of coral communities towards species that are more thermally tolerant. These species tend also to provide less structural complexity, with implications for habitat services to other species. Loss of live coral and degradation of habitat structure from bleaching will be exacerbated by increased physical disturbance from stronger storms and reduced coral calcification rates (due to ocean acidification). Reduced live coral cover will increase rates of bioerosion and therefore further losses to reef framework. Loss of coral reef habitat will have serious implications for reef-dependent species, and for the physical foundations of the entire GBR ecosystem (Fabricius et al. chapter 17).

Pelagic environments

Pelagic environments are important for the transport of propagules (such as eggs and larvae) and food resources. Planktonic assemblages are the basis of pelagic food chains and provide productivity hotspots for higher trophic groups (eg fishes, birds and whales) as well as the larvae and adults of benthic assemblages. Pelagic environments will be most affected by changes to ocean circulation, increasing sea temperature, ocean acidification and changes in ENSO. Their vulnerability is moderate, particularly because of the sensitivity of plankton to environmental changes, and the consequent implications for the productivity of the GBR ecosystem. Plankton communities are major primary producers and productivity on the GBR is strongly influenced by periodic events that alter nutrient availability for plankton, many of which will be affected by climate change. Corresponding changes in the dynamics of plankton communities are expected, with flow-on effects to higher trophic levels. Changes to planktonic communities will affect the pelagic larval stage of many reef-based and other marine organisms. If productivity becomes highly variable, recruitment population dynamics will become more variable, with extreme year classes becoming more common and population replenishment seriously impacted (Kingsford and Welch chapter 18).

Coastal habitats

Coastal habitats are an important interface between land and sea. They have a critical role in the connectivity of the GBR ecosystem, and provide nutrient cycling, primary production, biofiltration, critical habitat and coastal protection. Coastal habitats comprise estuaries, mangroves, salt marshes, beaches, wetlands, seagrass meadows and nearshore waters and reefs. They are moderately vulnerable to climate change, particularly sea level rise, changes to rainfall regimes and flood events, and increases in sea temperature. Changes to circulation patterns will also affect coastal habitats and have implications for the dynamics of larval supply to reefs and the degree of connectivity between reefs and the coast. Changes to ocean circulation patterns could also interact with changes in temperature and productivity to affect survival of pelagic larvae and condition at settlement. This could lead to impacts on the reproductive success of species dependent on coastal habitats, and affect dispersal of larvae (Sheaves et al. chapter 19).

Islands and cays

The more than 900 islands and cays form another significant habitat in the GBR, providing key breeding sites for seabirds and marine turtles as well as habitat for many endemic flora and fauna species. Islands and cays are particularly sensitive to sea level rise, changes to ENSO, increasing air temperature and changes to rainfall patterns. Due to their isolation and frequent remoteness, islands and cays are moderately to highly vulnerable to climate change. Implications for the GBR ecosystem include loss of critical habitat and breeding sites, particularly for protected species, and degradation of a unique component of the GBR seascape (Turner and Batianoff chapter 20).

24.1.6 Interactions between stressors

Interactions between climate and localised non-climate stressors are expected to create particularly damaging synergies, adding to concerns about climate change. For example, corals exposed to pollutants, turbidity, sedimentation or pathogens have been shown to be more susceptible to bleaching, or less able to survive a bleaching episode. Similarly, reefs that have fewer herbivores due to fishing pressure may recover more slowly after a bleaching event should macroalgae dominate the substrate after significant coral mortality. Furthermore, chronic local stressors – such as poor water quality – can affect the recovery potential of reef communities. This can result because fertilisation and larval recruitment in corals are particularly sensitive to environmental conditions, and because macroalgal growth rates increase in nutrient-rich waters[13]. The effects of elevated temperatures on corals can render them more susceptible to other pressures, for example disease, predation and the cumulative effects of other non-climate stressors. Similar synergies between stressors are likely to affect other species also, highlighting the urgent need to develop an integrated approach to reducing climate change impacts through building ecosystem resilience.

24.1.7 Historical perspective

The fossil record provides information on past climate conditions and climate change and how coral reefs responded over geological timeframes. This historical perspective shows that tropical marine ecosystems have experienced climate change of a magnitude comparable to (and in some periods greater than) the IPCC projections in their geological history. However, it also reveals that the *rate of change* expected over coming decades is unprecedented.

Coral reefs have endured throughout the fossil record, despite previous warming events. This highlights the natural resilience of these ecosystems over geological time scales despite large environmental variability (Pandolfi and Greenstein chapter 22). However, there is clear evidence of massive ecological shifts during these climatic changes, with prolonged periods (hundreds of thousands to millions of years) during which there were dramatically altered communities. For example, coral components of reef ecosystems are insignificant during the latter half of the Palaeozoic, with reefs instead dominated by algae that secreted high-magnesium calcite and aragonite skeletons (Pandolfi and Greenstein chapter 22). These dramatic changes and extended periods of recovery provide insights to the potential fate of present-day coral reefs under climate change scenarios.

While the paleoecological evidence suggests that the projected *magnitude* of climate change is not likely to result in the complete extirpation of coral reefs globally or locally, the significance of the projected rate of climate change is more difficult to ascertain. Further, today's coral reefs are exposed to a range of stresses that are unique to the modern era. The impacts of human activities have altered much of the marine environment in which coral reefs occur, undermining the resilience of these ecosystems[2,8]. Together, these factors suggest that *"…modern coral reefs might be much more susceptible to current and future climate change than is suggested by their geologic history"* (Pandolfi and Greenstein chapter 22).

24.1.8 Vulnerability of industries and regional communities

The GBR catchment area currently has a population of almost 850,000 people. While most towns and communities in the region have a strong economical dependence on agriculture, manufacturing and mining, several major communities – including Cairns City, Douglas Shire and Whitsunday Shire – depend on tourism as their major industry. Commercial, charter and recreational fishing, and land-based support industries, are other important industries in the region, contributing to the social fabric and economic opportunities in many regional communities. Aboriginal and Torres Strait Islander peoples have a strong presence in the GBR, relying on it for important cultural activities such as fishing, hunting and maintenance of ancestral linkages.

The benefits provided by the GBR to individuals, communities and industries include a range of ecosystem goods and services. These goods and services take the form of direct economic benefits (including commercial activities such as tourism and fishing), social services (including recreational activities and cultural linkages) and environmental services (including shoreline protection from barrier reefs and mangrove stands). Consequently, climate impacts on the GBR ecosystem are expected to be a significant mechanism by which GBR communities and industries are exposed to risks from climate change.

This assessment has found that, as for ecosystem components, the vulnerability of GBR communities and industries is a function of their sensitivity and exposure. Sensitivity is largely a function of the nature and strength of dependencies that regional communities and industries have on the natural resources[16]. Exposure results from changes to the availability of or access to the ecosystem goods and services on which communities and industries depend. In contrast to the ecological components of the GBR however, human communities have the capacity to anticipate change, prepare coping strategies and implement planned adaptation measures. For this reason, one of the most important determinants of vulnerability for communities and industries of the GBR is their adaptive capacity. The extent to which social and economic systems are able to maintain key functions and processes in the face of change – their resilience – is a key indicator of their vulnerability to climate change. The only recent study of coastal communities within the GBR region[5] investigated the likely adaptive capacity of communities and industries to climate change and identified three core issues:

i) Community members vary in their recognition and acknowledgement of climate change

ii) GBR industries vary in their understanding about climate change and climate change processes

iii) Greater awareness about climate change is needed before industries and communities can identify the consequences, impacts or possible responses to climate change

The Fenton and Beeden study found these issues existed for all groups or sectors interviewed: Traditional Owners (Aboriginal people), commercial and recreational fishing, tourism, regional natural resource management organisations, and coastal development and planning.

Traditional Owners

For thousands of years, Aboriginal and Torres Strait Islander people have fished, hunted and gathered in the waters, adjacent coastal areas, and on the islands in the area that today we know as the Great Barrier Reef. They relied on these areas for traditional resources and customary practices, and recognise many important cultural sites and values throughout the GBR. Today there are some 70 Traditional Owner groups along the coast from the Torres Strait to Bundaberg with an interest in, and connection to, coastal land and the GBR. Almost 55,000 Indigenous people live along the GBR coast or within the GBR catchment, which equates to 50 percent of all Indigenous people in Queensland. Access to country (including sea country), maintaining cultural identity, and the continued maintenance of traditional hunting rights for sustainable use of marine resources are three critical issues of current concern to Traditional Owners within the GBR catchment area.

Traditional Owners identified increased air temperature as a major concern associated with climate change. Changing temperatures are likely to alter the seasonality and availability of marine resources on which they depend for traditional hunting and gathering. Other concerns included the potential loss of totem species, such as dugong and marine turtles, and displacement of coastal Traditional Owner communities due to rising sea levels.

These concerns indicate moderate sensitivity and moderate to high exposure to climate change. However there were indications of high adaptive capacity among Traditional Owners. This could stem from their cultural experience with long-term changes, such as sea level rise over their 60,000-year history. Although further work is needed to obtain a reliable measure of resilience, this assessment did reveal among at least some Traditional Owners a pragmatic attitude to change that has the potential to significantly moderate their vulnerability to climate change.

Tourism

The GBR tourism industry, as part of regional tourism, contributes A$6 billion to the Australian economy through some 20 million visits to the region and over 1.9 million visits to the GBR with commercial operators[1]. There is considerable diversity in the GBR tourism industry, ranging from high speed vessels carrying hundreds of passengers for day trips to large pontoons, through cruise ships, sailing or fishing charters, island resorts and kayak tours.

The tourism industry regularly deals with fluctuating visitation to the GBR while having to contend with changes in the quality of many reef sites due to coral bleaching, poor water quality and the impacts of crown-of-thorns starfish. This direct experience with changes in resource quality, coupled with the strong dependency of many sectors of the tourism industry on high ecosystem quality, render them especially aware of their sensitivity and exposure to climate change impacts. As a result, tourism operators were found to be actively concerned about the impacts of climate change on their businesses and livelihoods, and indicated a willingness to prepare for any potential climate change impacts.

Some of the key sensitivities to climate change identified by the tourism industry[a] include degradation of reef sites due to temperature-induced coral bleaching, poor recovery of degraded sites as a result of other stressors such as water pollution, and deteriorating ocean-going conditions due to increased storm activity. One of the other major concerns for tourism operators was the potential for the GBR to lose its marketing advantage as a high quality reef destination as a result of climate change. Even though other reefs around the world are likely to have similar or even greater vulnerability, the profile given to climate change impacts on the GBR (especially coral bleaching) was seen to impose some

a GBR Marine Tourism Operators Forum on Climate Change, November 2005 level of business risk through its potential impacts on destination appeal, and therefore on market share. In combination, these issues amount to the tourism industry having both high sensitivity and high exposure to the effects of climate change.

Potential impacts from climate change can be expected to be offset, somewhat, by the high adaptive capacity of the tourism industry. The industry's strong awareness of the risks, and early indications of their willingness to identify and pursue strategies of mitigation and adaptation suggests a high level of resilience. Examples of this adaptive capacity include industry investment in understanding the risks from climate change and development of a GBR Tourism and Climate Change Action Strategy[b]. Mitigation strategies that tourism operators are considering include reducing their climate footprint through use of biodiesel fuels, sail or solar power and purchasing carbon offsets for their greenhouse gas emissions. Examples of adaptation strategies that tourism operators are contemplating include revising marketing strategies to ensure they accurately reflect the condition of tourism reefs (to avoid discrepancies between the expectations and actual experience of tourists), active enhancement of tourism sites through maintenance of corals and feeding to attract fish, and relocating operations to less vulnerable sites. The total economic impacts of climate change may be reduced to some extent by substitution effects, such as shifts from reef-based tourism to beach holidays, water sports or other activities that are less dependent on reef quality[1].

Fishing

There are five main commercial fisheries operating in the GBR that together catch about 24,000 tonnes of seafood each year, and have a total gross value of A$251 million[1]. Recreational fishing is also a major activity. There are estimated to be about 800,000 recreational fishers in Queensland, and those using the GBR contribute about A$623 million to the Australian economy annually[1]. These fishers are estimated to have an annual catch of 3500 to 4500 tonnes.

Fishing, particularly commercial fishing, is highly sensitive to any changes in fish availability or access to fisheries resources that may result from climate change. This vulnerability assessment found that the adaptive capacity of fishers appears to be generally low (Fenton et al. chapter 23). Interviews with fishers indicated that there was little preparedness in the commercial fishing industry and recreational fishing sector to respond to the impacts of climate change. This appears to be in some part due to the recent increase in regulations, which have been implemented to increase the resilience of the GBR ecosystem, and thus safeguard fisheries for the future. Commercial and recreational fishing have been regulated in recent years with the introduction of legislation such as the Fisheries (East Coast Trawl) Management Plan (1999), Fisheries (Coral Reef Fin Fish) Management Plan (2003), new *Environment Protection and Biodiversity Conservation Act* (1999) guidelines and the new Zoning Plan for the GBR (2003). The new Zoning Plan increased highly protected areas (which are closed to fishing) from 4.5 to 33 percent[4]. Consistent with reports on fisheries from other parts of the world, many GBR fishers expressed a strong belief in their adaptive capacity, yet few indicated preparations were being made in anticipation of climate change.

This assessment found that the commercial and recreational fishing sectors were characterised by high sensitivity and moderate to low adaptive capacity. Direct exposure to changes in cyclone and

b Coordinated by Queensland Tourism Industry Council storm activity is likely to be an area of concern, affecting access to sites and the number of fishing days. However, a definitive assessment of their vulnerability to climate change is difficult at present due to the large knowledge gaps about exposure. While this assessment has found that many species of fish, including those targeted by fishers, are vulnerable to climate change as a result of increases in sea temperature, changes in ocean circulation and loss of habitat, it was unable to predict the magnitude of these impacts, or the resultant economic impacts. Until quantitative estimates of changes to abundance, size and distribution of target fish species are developed, it will remain difficult to assess the vulnerability of commercial and recreational fishing to climate change. This knowledge gap is also likely to hamper the adaptive capacity of fishers.

Regional natural resource management

Regional Natural Resource Management (NRM) bodies have an important role in identifying community aspirations for maintaining the natural resources in the coastal catchments of their regions adjacent to the GBR. Queensland NRM organisations have developed regional plans, which identify management targets and associated actions to address critical NRM issues. Many of the plans currently do not incorporate climate change as a driver for their management actions, nor do they commonly include management actions in response to climate change. This may reflect that NRM plans were mostly developed several years ago, when awareness of the importance of climate change to NRM issues was relatively low within the broader community. Clearly, NRM processes will need to take account of climate change issues if they are to respond to the threats that climate change poses to natural resources in the coastal catchments of the GBR.

Coastal development and planning

Coastal development and planning appear to be highly vulnerable to climate change. Despite widespread recognition of the sensitivity of coastal infrastructure, and its high exposure to sea level rise and increased storm intensity, adaptive capacity appears low at present. Clearly, major vulnerabilities exist, especially if higher sea level rise estimates are correct. This assessment has identified that political and institutional constraints appear to be key impediments to planned adaptation to climate change. Community members and officials involved in coastal issues already cited significant investment (eg infrastructure) in vulnerable coastal areas and limited evidence of decision-makers to limit ongoing coastal development in flood prone or storm surge areas of the coast. The soaring desirability of seaside properties and their commensurate value continues to create powerful incentives for development in the coastal strip, resulting in high – and increasing – vulnerability to climate change.

24.2 Potential management responses

This assessment has found that vulnerability of the GBR takes many forms, with climate change predicted to affect species, habitats, processes and human systems in varied ways. Consequently, climate change threatens to undermine or modify the ability of the ecosystem to deliver the goods and services upon which regional communities and industries have come to depend. This not only has implications for those directly affected, but for the government organisations responsible for managing the natural resources.

As the Australian Government agency responsible for planning and management of the GBR, the goal of the Great Barrier Reef Marine Park Authority (GBRMPA) is the *'long-term protection, ecologically sustainable use, understanding and enjoyment of the Great Barrier Reef through the care and development of the GBR Marine Park'*. Recent initiatives to improve water quality and to increase protection of biodiversity were taken to help meet this goal. However, climate change brings a new suite of pressures to the GBR. The global nature of the threat, and its relatively recent emergence, make climate change a serious challenge for marine protected area managers, as well as for the ecosystems in their care.

Despite these challenges, marine protected area managers have an important role in addressing the threats posed by climate change. Through partnerships with scientists, communities and industries, management agencies such as the GBRMPA are playing a lead role in efforts to maintain the capacity of tropical marine ecosystems (and the industries and communities that depend on them) to cope with climate change.

The many experts who have compiled the vulnerability assessments in this book also suggested strategies to reduce the vulnerability of key habitats and species groups. This section summarises their recommendations for adapting management of the GBR to climate change, which fall into two broad categories: promoting mitigation and supporting resilience.

24.2.1 Mitigation of climate change

Mitigating the rate and extent of climate change is repeatedly identified throughout this vulnerability assessment as a priority issue that must be addressed if the GBR is to cope with climate change. There is no component of the GBR ecosystem that is not sensitive to the effects of climate change, and reducing the amount of change that occurs is the single most effective way of minimising negative impacts. The rate of climate change is also important in determining the scope for adaptation; mitigation helps buy time for adjustments that can reduce the damage caused by climate change[7]. Further, the extent of climate change – the maximum level of stress attained – determines the risk of irreversible damage occurring. If critical thresholds are reached, no amount of investment in resilience can prevent serious damage to certain ecosystem components, the organisms that depend on them and the goods and services that they provide. Mitigation and resilience-building are, therefore, complementary strategies: both are necessary if tropical marine ecosystems are to cope with climate change[15]. Mitigation becomes particularly important for the maintenance of habitat components of the GBR ecosystem, such as coral reefs, pelagic environments, coasts and islands, which have limited capacity to recover should climate change cause particularly serious damage. For these reasons, mitigation is a central issue for the GBR and its management.

Opportunities for marine protected area managers to contribute to mitigation efforts can take a number of forms, centering on communication (information and awareness-raising) and demonstration (taking measures to reduce the climate footprint of activities on the GBR). Management agencies such as the GBRMPA are looked to as authoritative sources of information about the potential impacts of climate change on coral reefs and associated ecosystems. The GBRMPA has played a key role in raising awareness about the vulnerability of the GBR to climate change, and in ensuring a balanced and scientifically robust knowledge base for decision-makers. As this assessment has shown, there is an urgent need for further action on many fronts to reduce the vulnerability of the GBR.

The expert contributions to this assessment unanimously agree that one of the most decisive elements in the future of the GBR is the rate and extent of climate change that eventuates. In this regard, managers have a direct stake in the success of mitigation efforts. Using knowledge about the implications of climate change for tropical marine ecosystems as a basis for setting mitigation targets and communicating mitigation efforts is becoming core business for managers like the GBRMPA. Further, management organisations and their partners have the opportunity to demonstrate a commitment to reducing their own climate footprint in support of more global mitigation efforts. Initiatives to reduce greenhouse gas emissions by reef-dependent industries such as tourism are already underway, and these can inspire others to reduce their climate footprint.

24.2.2 Supporting ecological resilience of the Great Barrier Reef

It is inevitable that climate change will continue to cause degradation of the GBR over coming decades. However, this assessment has found that non-climate stressors are exacerbating the effects of climate change for nearly every component of the ecosystem. In many cases, other stressors increase the susceptibility of organisms to climate change. Even where these stressors do not have a synergistic effect with climate change, they have an additive effect. Climate change is likely to bring many populations close to critical thresholds; reductions in the cumulative effects of other sources of stress could be critical in preventing these tipping points from being reached.

Despite being one of the healthiest tropical marine ecosystems in the world, the GBR is under pressure from a variety of human activities. These interact with climate change, often to exacerbate its effects. Key issues in this regard include catchment uses that result in degraded water quality, coastal development and other activities that constrain future adaptation of species and habitats (eg coastal development that acts as a barrier to future landward migration of mangroves as sea level rises). These local pressures act to reduce the resilience of the ecosystem, undermining its ability to cope with climate change.

Many of the management recommendations presented in this assessment accord with well-established principles for supporting resilience of tropical marine ecosystems[18,8] (McCook et al. chapter 4): reduce stress from water pollution, protect biodiversity, protect key functional groups (such as herbivores) and protect refugia. Significantly, however, this assessment increases the justification for key resilience-building strategies through a deeper understanding of the specific actions and benefits that resilience-based management entails. It also identifies strategies for improving the resilience of particular species groups that are vulnerable to climate change.

While many of the management strategies identified in this vulnerability assessment are already being undertaken, the impacts of climate change will increase the urgency to ensure these actions are successful. The following section presents a synthesis of the management recommendations offered by the experts who have contributed to this vulnerability assessment.

Reduce stress from poor water quality

Degraded water quality can be one of the most significant impacts on resilience. Toxicants such as pesticides, and high concentrations of nutrients and sediments, all have the potential to acutely stress many tropical marine organisms. Additionally, and perhaps most importantly, these stressors can have chronic impacts, affecting the ability of organisms to cope with the effects of climate change.

This vulnerability assessment has found that the negative interaction between climate stressors and poor water quality – which in many cases is synergistic – has the potential to seriously undermine the resilience of nearly every component of the GBR ecosystem. For example, the resilience of coral communities is particularly challenged in areas where water quality is degraded, as chronically stressed corals are much less able to recover from bleaching events. Further, coral communities exposed to excess nutrients and sediments have substantially increased recovery times following major mortality events. Improving the quality of water entering the GBR will be a major contribution towards increasing the ability of communities such as corals and seagrass to cope with, and adapt to, climate change.

This assessment has also identified many other plants and animals whose vulnerability to climate change can be reduced through improvements to water quality. Fertilisers and pesticides entering the GBR can have prolonged impacts on plankton communities, seagrass meadows and fish. Microbial communities, which play critical roles in primary productivity, nutrient cycling and facilitation of other key processes like recruitment, are sensitive to nutrients and trace metals, which find their way from the land into the marine environment via freshwater ecosystems. Rivers and localised point sources such as sewage outfalls are sources of toxins and pathogens, which are known to increase the prevalence of diseases in higher animals such as dugong. Reducing levels of particular contaminants that affect microbial communities and increase disease prevalence (such as trace metals and nutrients) can offer a targeted approach to water quality management in the context of climate change.

Climate change is also expected to result in greater intensity of rainfall events, leading to increased risk of erosion and flooding. Efforts to stabilise land areas prone to erosion and investment in strategies to trap sediments and nutrients in the coastal zone (before they enter the marine environment) will become increasingly important in the face of climate change. Toward this end, restoration or protection of mangroves and associated wetlands, and more stringent controls on coastal development, would be a significant contribution to the ability of the GBR ecosystem to cope with climate change.

Improving the quality of water entering the GBR is the goal of the existing Reef Water Quality Protection Plan. The Plan, which is an agreement between the Australian and Queensland governments, aims to halt and reverse the decline in water quality in the GBR by reducing inputs of diffuse sources of pollution and improving catchment capacity to capture and filter pollutants before they enter the GBR. This includes identifying water quality targets for key contaminants through regional NRM plans. These targets and management responses are being developed by the respective regional NRM bodies and will need to reflect the current awareness of the significance and pervasiveness of the effects of climate change. This assessment makes it clear that improvements to water quality are now more important than ever for the future health of the GBR. The emergence of climate change as a dominant threat to the GBR, and the significance of synergies between climate stressors and water quality, highlights the importance of efforts to halt and reverse the decline in the quality of water entering the GBR lagoon.

This vulnerability assessment also provides the foundations for more targeted responses to water quality issues. Not all aspects of water quality interact similarly with climate change, and the significance of interactions varies in space. An urgent priority for management-oriented research is an analysis of the relative importance of different aspects of water quality in determining the vulnerability of key species to climate change. An integrated and spatially explicit understanding of the resilience of the GBR to climate change would assist managers to prioritise investment of limited resources to maximise the resilience outcomes for the GBR (such as through targeted water quality improvements). This integration is limited primarily by a lack of information on what pollutant loads are being delivered to different parts of the GBR in the context of high-value and high-risk environments. There is a need to incorporate water quality discharge information into current hydrodynamic and receiving-water models.

Protect key functional groups

A consistent finding of this vulnerability assessment is that the GBR ecosystem will be subjected to increasingly frequent and severe stressful impacts. As a result, the ability of populations, species and communities to recover from damage will become critical for the future of the GBR. Recovery processes are frequently highly sensitive to disturbance, highlighting the importance of identifying and protecting the functions that are essential for recovery. One function that has frequently been highlighted as of central importance to the resilience of tropical marine ecosystems is herbivory. In both observational and experimental studies[8,9,13], herbivores have been shown to be one of the most important functional groups for maintenance of coral-dominated reef ecosystems globally.

In the GBR, herbivores are not currently fished on commercial scales. Measures to ensure the ongoing protection of populations of herbivorous fish in the GBR are in place. Current commercial gear and methods used on reefs (eg line) are not suitable for catching herbivorous fish and there are restrictions on the use of methods that target reef herbivores in commercial scales (eg net). The capacity for future growth of a commercial scale herbivore fishery in the GBR is limited, and consideration of the important role of herbivorous fishes in climate change resilience should be included in future examinations of fisheries legislation and ecosystem-based management approaches.

While the importance of herbivory to the functioning of the GBR ecosystem has been a focus of research in recent years, many other species groups are also likely to play an important role in resilience. Although less studied, higher trophic species, such as sharks, rays, other predatory fishes, seabirds and marine mammals, exert important top-down controls on trophic systems. These predators selectively remove individuals from prey populations that are less well adapted to their environment. Without this selective pressure, it is possible that many lower-trophic species will take longer to adapt to changes in conditions associated with climate change. Therefore, measures to avoid overfishing of demersal predators (such as coral trout and emperors), pelagic species (such as tunas and mackerels) and sharks are likely to play a significant role in maintaining the resilience of tropical marine ecosystems.

Management regimes already exist for fisheries in the GBR. Fisheries across Australia are gradually aligning with the national standards for ecosystem-based management, via mandatory three to five year assessments under the *Environment Protection and Biodiversity Conservation Act* (1999). The first round of assessments have been completed for all GBR fisheries, resulting in acknowledgement that substantial improvements have already occurred but some recommended actions, while agreed to, are yet to be implemented. While climate change concerns were not the driver for this process, these national standards represent a significant tool for maintaining ecosystem resilience. Climate change gives added importance to the timely implementation of ecosystem-based fisheries management plus other important strategies, such as industry led stewardship initiatives.

Protect refugia

One of the greatest virtues of the GBR in the context of climate change is its immense size and complexity. The expanse and diversity of the ecosystem helps ensure that there is a high level of response diversity, even to global stressors like climate change[8] (McCook et al. chapter 4). The size and complexity of the ecosystem means that there is a high chance that some areas will remain undamaged, or at least will survive in a good enough condition that they are able to act as a source of recovery for areas damaged by climate change. These refugia may be protected from the full impacts of climate change due to physical conditions (such as proximity to upwelling of cooler water or exposure to strong currents), biological qualities (such as a community dominated by bleaching resistant corals) or they might be fortunate by being located in an area that receives lower levels of climate-related stress[15]. Whatever the basis for their resilience, these sites are highly important to the ability of the ecosystem to sustain itself in the face of climate change.

The experts who contributed to this vulnerability assessment highlighted the importance of identifying potential climate change refugia within the GBR, and of ensuring their protection from other stressors. As the effects of climate change manifest themselves through degradation of the GBR over coming decades however, these refugia will also become focal points for industries and other users seeking high quality reef locations. The concentration of use (including tourism, commercial fishing and recreational use) has the potential to substantially increase the risk of local impacts to these areas, compromising their role as climate change refugia. Effective management of marine protected areas under a changing climate will increasingly involve careful monitoring and control of use of activities that otherwise might threaten these refugia[15].

The current zoning plan for the GBR protects representative examples of 20 percent or more of each of the 70 identified bioregions from all extractive uses (including fishing), protecting approximately 33 percent of the GBR Marine Park in total. These areas have been identified by a rigorous process using the best available scientific information. However, the overlap of these highly protected areas with the location of climate change refugia cannot be taken for granted, and should be a focus of future research effort and zoning reviews.

Restore resilience of particular species groups

This vulnerability assessment has identified a number of opportunities for reducing the vulnerability of particular components of the ecosystem. The recurrent recommendation from the experts contributing to this assessment is that the best chance for minimising the impacts of climate change is through measures to reduce other stressors. Here we synthesise the strategies recommended by authors for supporting the resilience of particularly vulnerable components of the ecosystem: marine turtles, seabirds, fish species, marine mammals, seagrass meadows, islands and coastal habitats.

Marine turtles

The GBR is an important habitat for marine turtles, and all six species found in the GBR face serious conservation threats at the global scale. While at evolutionary time scales climate change is not a new threat, the combination of climate driven impacts and existing anthropogenic pressures will increase the long-term risk to these iconic reptiles. Increasing air temperatures have the potential to bias the gender ratio of marine turtle hatchlings, while sea level rise threatens traditional nesting beaches.

This assessment has concluded that the effects of increased air temperatures and sea level rise on turtle nests, coupled with human-induced changes in patterns of sand deposition and erosion, and encroachment of human settlements, limit the availability of alternative nesting beaches for marine turtles. Strategies that maximise long-term nesting success – such as planning for shifts in turtle nesting beaches or timing of breeding seasons, reducing beach erosion, removing feral predators and maintaining current and future 'turtle friendly' beaches – will help maximise the adaptive capacity of turtles in the context of climate change. If beach sand temperatures increase to levels consistently above the lethal threshold for embryo development, the viability of turtle populations may depend upon strategies to restore or protect critical habitats (eg increasing shading at nesting beaches, relocating nests to cooler zones or limiting other disturbances). These issues highlight the importance of building climate change considerations into management regimes for coastal areas, including processes for assessing proposed coastal development projects and other activities that might reduce the adaptation options for nesting marine turtles.

Seabirds

The islands and waters of the GBR provide nesting and foraging sites that are critical for many species of seabirds. However, climate change will compromise the ability of the GBR to sustain local populations and measures need to be taken to minimise non-climate stressors at nesting sites and foraging grounds. This assessment identified a number of strategies that should be explored to help protect the ability of seabirds to adapt to climate change. Island management plans that acknowledge the potential for shifts in the timing or duration of bird breeding seasons can facilitate control of human activities that impose additional stress on nesting birds. Birds may also need to shift to alternative breeding sites in order to adapt to climate change, and efforts to identify and protect current and potential future nesting sites will support the resilience of seabirds. Other strategies to increase resilience include maintaining or restoring site qualities that promote nesting success (such as ground-cover or beach profiles). Similarly, measures to address the risk of provisioning failure could also reduce the vulnerability of seabirds to climate change. Such measures might include review of stock assessment priorities and fisheries management measures to ensure fish forage resources (especially bait fish) and pelagic predatory fish (such as tunas and mackerels, which play an important role in making bait fish accessible to foraging seabirds) are adequately protected during unusually warm summers.

Fishes

While many species of fish are vulnerable to climate change, either through direct or indirect effects, the greatest potential for reducing vulnerability through management actions lies with those species that are commercially and recreationally fished. The expert assessment of vulnerability of fish to climate change identified the potential for catch levels that are thought to be currently sustainable to become unsustainable in the future as environmental conditions change. For many species, especially sharks, there is inadequate information for determining population status, let alone sustainable catch levels. Better understanding of current population sizes through improved stock assessments is an urgent priority for many fishery species. However, even current levels of knowledge about climate change vulnerability (and the information gaps) have the potential to improve the long-term sustainability of fisheries if incorporated into fisheries assessments and management plans.

The experts contributing to this vulnerability assessment universally highlighted the existence and significance of knowledge gaps relating to climate change. For this reason, many contributors recommended a management approach that is risk-based, precautionary and adaptive to changing conditions and knowledge. The situation relating to sharks and rays (minimal information about population status but confidence in assessment of high vulnerability) highlights the importance of making allowances for knowledge gaps. Further, efforts to minimise destruction of important habitats (particularly coastal and estuarine nursery areas) and incidental mortality (such as in beach protection and fishery bycatch) will complement fishery-based strategies. Measures that protect known and potential predator diversity hotspots from fishing pressures, particularly those in the pelagic environment, were recommended for building the resilience of predator populations to climate change.

Marine mammals

The GBR supports more than 30 species of marine mammals, some of which are threatened with extinction globally. While all marine mammals are already protected by a number of international treaties and laws within GBR waters, they remain under a range of stressors that act to exacerbate their vulnerability to climate change. This assessment has identified a number of non-climate stressors that affect marine mammals, including net entanglement, displacement from feeding areas, boat strike, marine debris, tourism and Indigenous hunting. Most of these stressors are already the focus of management initiatives. However, the emergence of climate change and associated additional stressors increases the imperative for measures to increase protection of marine mammals. Additionally, many of the main food resources for mammals (seagrass, plankton and fish) are also vulnerable to climate change. Strategies that protect the food resources of marine mammals will be important to their ability to cope with climate change.

Seagrass meadows

Dugong and other species that depend on seagrass meadows are vulnerable to climate change due to the sensitivity of seagrass to climate change. Many seagrass meadows are already subject to stressors associated with coastal development and changed sediment regimes, and climate change is expected to increase their vulnerability. Measures that reduce the amount of sediment deposition and turbidity (maximise light penetration) are likely to be influential in reducing the vulnerability of important seagrass habitats, especially in coastal areas. Land management and coastal development plans that support these measures are likely to be important for the long-term sustainability of seagrass meadows. This will be particularly important for species like dugong, as populations along the urban coast are already less than five percent of what they were 40 years ago and declines in seagrass could have catastrophic consequences. Although less is known about inshore dolphin populations, their dependence on seagrass meadows also makes maintenance of this habitat critical.

Island and coastal habitats

Key issues for island management that will become more critical as a result of climate change are weed infestation, pest and disease outbreaks, fire regimes, storm surge, erosion, dredging and other development activities. Island management plans that explicitly consider the changing risk profile for these threats will help reduce the vulnerability of island ecosystems to climate change.

Mainland coastal habitats share many of the vulnerabilities to climate change with islands of the GBR. While terrestrial ecosystems have not been included in this vulnerability assessment, management of coastal habitats will play an important role in the vulnerability of the GBR to climate change because of connectivity within the ecosystem. In particular, important coastal habitats such as mangroves and salt marshes are highly vulnerable to sea level rise and changes in weather patterns. The sustainability of these habitats will depend in a large part on their ability to migrate landward as conditions change, yet increasingly there are barriers to such movement. Similarly, coastal developments, agriculture and other infrastructure projects limit the movement of more mobile species (such as fish) within and between coastal habitats. Removal of coastal barriers, and acquisition or rehabilitation of coastal lands are likely to become important to the future of coastal habitats. Management strategies that protect existing intact coastal habitats, remove and prevent further barriers being established, and reinstate adaptation options will become increasingly important to the management and conservation of coastal ecosystems.

Protected species

Species such as whales, dolphins, dugongs and marine turtles are listed as threatened or protected by international, national or state legislation and treaties. Some species of seabird are also listed under international treaties such as the Japan-Australia Migratory Bird Agreement and the China-Australia Migratory Bird Agreement. These intergovernmental processes are based on set criteria to assess threats to species. While there are few species for which there is quantitative data on the threat of climate change, the processes are sufficiently flexible to allow consideration of climate change threats if they can be quantitatively demonstrated. The experts who contributed to this assessment highlighted the value of including climate change considerations in intergovernmental processes that aim to protect and conserve these species in the context of climate change.

24.2.3 Facilitating social and economic resilience

Changes to the GBR ecosystem will inevitably affect the communities and industries that depend on it. Coastal communities from Bundaberg to the tip of Cape York and the Torres Strait are dependent on the GBR as a major source of income and lifestyle. Industries such as marine tourism and fisheries (recreational, commercial and charter) rely on a healthy ecosystem and the goods and services it provides. Coastal communities also rely on the GBR for recreational opportunities, and for indirect benefits such as coastal protection. The magnitude of the impacts of climate change will depend in large part on the resilience of these communities and industries to the effects of climate change.

One of the most critical aspects of resilience in social systems is adaptive capacity. Resilient social systems have the ability to learn and adapt[6,17], and resilient people and communities recognise, learn and even benefit from the new possibilities that change brings. Regional communities and industries are affected by a multitude of factors operating at multiple scales in time and space. While climate change imposes discrete pressures on people who depend on the GBR in some way, its effects are mediated by the interactions they have with society, economy and the environment. Understanding the social and economic conditions, and regulatory environment, in which people operate can help understand their capacity to adapt to challenges such as climate change. Initiatives to address factors that undermine the adaptive capacity of social systems will increase the resilience of GBR industries and communities to the impacts of climate change.

This section summarises the findings of the contributing experts in relation to the main barriers to adaptation, and presents their recommendations on the potential strategies for decreasing socio-economic vulnerability by facilitating the adaptive capacity of social systems.

Coastal communities

An important observation of this vulnerability assessment relates to the way individuals distance climate change issues. Fenton and Beeden[5] found that there was widespread awareness of the potential for climate change to cause social and economic impacts. The concern, however, seemed to be directed at a community or industry level: community members tended to objectify climate change as a third-party issue, rather than as one that required their personal response. This may be a mechanism for coping with the threat or for resisting change[11,12], or it may reflect a belief that the major impacts will not manifest in their lifetime. More accessible information about potential impacts and opportunities for personal action, presented in a more compelling way, may help remove barriers to behavioural change.

When considered at a broader systems level, climate change has the potential to cause economic and social instability throughout the GBR region. Changes to reef condition, weather patterns and coastal hazards are expected to drive changes in the structure and viability of industries, the demographic characteristics of communities and the adequacy of key social infrastructure such as health care and sanitation[3]. Formal and informal institutions will need to adapt to these changing conditions, preferably in a proactive manner if many of the worst social and economic impacts are to be avoided. Effective partnerships and coordination of efforts across government agencies and non-government organisations will become increasingly important if coastal communities are to successfully adapt to climate change.

Traditional Owners

Traditional Owners have the longest association of any people with the GBR, and an extensive understanding of climate. This knowledge can provide insights into future change as well as temper the potential vulnerability of Traditional Owners through their cultural links with land and sea. Traditional Owners and their relationship with sea country in the GBR are subject to a multitude of pressures, potentially increasing their sensitivity to social and cultural impacts from climate change. Strong partnerships between government and Traditional Owners will help identify potential strategies for minimising the impacts of climate change on the relationship between Traditional Owners and their sea country.

Tourism

The GBR tourism industry is highly sensitive to the changes in resource quality and accessibility (due to weather conditions) that are predicted to result from climate change. At the same time, the industry appears to have good potential for adapting, which may offset some of the effects of climate change. However, a certain degree of economic impact from climate change is unavoidable. The extent of impact will depend, in part, on the nature and size of barriers to industry adaptation, such as market limitations, regulatory controls and financial constraints. Management arrangements that allow flexibility for tourism operators to adapt to change will become increasingly important to industry sustainability. However, social and environmental tradeoffs may need to be made in the GBR in response to climate change, as not all adaptation options that suit the tourism industry are compatible with ecological resilience or existing management policies. Close partnerships between managers and tourism operators will be used to identify strategies that facilitate adaptation by the tourism sector while also maximising the resilience of the GBR ecosystem.

Site-based interventions are another type of adaptation strategy being considered by reef-based industries. Although not to be considered as ecosystem management strategies, these types of intervention strategies may prove to have a role in helping sustain reef-based businesses in the face of climate change. For this reason, the GBRMPA is supporting efforts by leading tourism operators to develop and test site-based interventions, including strategies to reduce the severity of coral bleaching that occurs at small, high-value tourism sites. Tourism operators have also begun to consider the possibility of enhancing recruitment of corals at degraded sites. However, critical issues of genetic and ecological compatibility, and of economic and logistical feasibility, need to be resolved before such strategies can be implemented. Intensive reef enhancement or maintenance strategies face numerous challenges – not least of which are cost effectiveness and success rates – and they are not likely to be applicable at scales that can contribute to ecosystem resilience.

Fishing

One of the major issues for commercial and recreational fishing in the context of climate change is the limited knowledge about the vulnerability of most of the fisheries. This stems, largely, from a paucity of data on the magnitude of change likely to occur to important fish stocks. Given this assessment found fishing industries to be sensitive to climate change, with relatively low capacity for adaptation (at least at present), there is a need for better estimates of exposure to climate change. Partnerships between fisheries managers and stakeholders will enable the development of indices for vulnerable fisheries, using the best available information. This will assist with assessing the direction and magnitude of climate-induced change to stocks of important species. This knowledge can then be used to underpin the development of adaptation strategies that will increase the resilience of fishing industries to climate change. Partnerships between management and various fishing sectors will be important for the adaptation of fisheries and developing best practice approaches that will contribute to ecosystem resilience.

24.3 Policy responses to climate change

Climate change and its effects on social and natural systems are now mainstream issues receiving priority attention in international and national policy settings. Coral reef ecosystems are recognised as among the most sensitive of the earth's ecosystems, but they are also seen as important indicators of change, and a valuable focus for exploring and testing management responses to climate change. The emerging prominence of tropical marine ecosystems in climate change science and policy circles has led to calls for action from a diversity of arenas.

24.3.1 The international call to action

Through the International Coral Reef Initiative (ICRI), four important policy statements have called for international action in relation to mass coral bleaching events and climate change. In 1995, ICRI issued a 'Call to Action' that identified 'the potential adverse effects of climate change' as one of four key threats to coral reefs. Three years later, the worldwide impacts of the 1997–1998 mass coral bleaching event had further heightened concerns about the seriousness of climate change as a threat to coral reefs. This was reflected in the 'Statement on Coral Bleaching' issued at the International Tropical Marine Ecosystem Management Symposium (ITMEMS), a four-yearly summit meeting sponsored by ICRI. By 2003, the international coral reef community had recognised the need and ability to manage for mass coral bleaching. The concluding statement of ITMEMS 2 was 'coral reefs of the world have been deteriorating from coral bleaching and mortality due to warming seas' and that managers can 'address these trends by adopting a number of risk management strategies'. This trend – of moving from a call for research to a call for management – continues with the release of the Action Statement at ITMEMS3, held in late 2006. The statement, endorsed by 324 of the world's leading tropical ecosystem scientists and managers, from 45 countries, concludes that 'climate change is now recognised as one of the most serious long term threats to the biodiversity and services provided by tropical marine ecosystems'. Significantly, it also states that 'managers can take action to reduce the impacts of climate change in tropical marine ecosystems' (see box).

The Convention on Biological Diversity (CBD) has also called for management, research, capacity building and financing of activities that address climate change and its impacts on coral reefs. The CBD has catalysed national efforts to consider climate change-related impacts on biodiversity. In 1998, the CBD formed a Subsidiary Body on Scientific, Technical and Technological Advice, which developed a Specific Work Plan on Coral Bleaching. At the 2004 CBD Conference of Parties, this work plan was updated with a category for 'Management Actions and Strategies' on coral bleaching.

Recommendations relating to climate change in:
ACTION STATEMENT
from the
THIRD INTERNATIONAL TROPICAL MARINE ECOSYSTEMS MANAGEMENT SYMPOSIUM
Cozumel, Mexico
20 October 2006

ITMEMS3 recommends that:

- Managers should promote action to limit climate change to ensure that further increases in sea temperature are limited to 2°C above pre-industrial levels and ocean carbonate ion concentrations do not fall below 200 micomol per kg
- Management planning must incorporate recognition that mass coral bleaching, will have the potential for similar social and economic consequences as other environmental disasters such as droughts, oil spills and other disasters, and will require similar responses
- Facilitate and finance actions to increase resilience of coral reef social-ecological systems, particularly through marine management area networks comprising adequate areas of coral reefs and associated habitats in non-extraction zones, protection of water quality and herbivore populations, and adaptive governance
- Facilitate and finance the development and implementation of coral bleaching response programs, including contingency funding
- Increase investments in targeted messages to accelerate adaptation to climate change
- Invest in village-to-global education and communication for climate adaptation that will integrate traditional and scientific knowledge into implementation of adaptation strategies for coral reefs around the world.

Building on these resilience efforts, the GBRMPA, in partnership with the Australian Greenhouse Office, established the GBR Climate Change Response Program. Established in December 2004, this A$2 million program has been at the forefront of endeavours to understand the implications of climate change for tropical marine ecosystems and to develop management responses. One output of this program is *A Reef Manager's Guide to Coral Bleaching*[14], which was produced in conjunction with the US National Oceanic and Atmospheric Administration to assist coral reef managers worldwide to adapt to the issues relating to climate change impacts.

Communication and engagement with community and industry is a key priority for the GBRMPA, which has built strong partnerships with major stakeholder groups in the GBR region. These have lead to the formation of a GBR Tourism Climate Change Action Group and the drafting of a GBR Tourism and Climate Change Action Strategy. Despite these successes, there are indications of persistent confusion among stakeholders about the implications of climate change. This highlights the value of a strategic and consistent approach to communicating the impacts, implications and current and future management responses to climate change with stakeholders and the broader community.

This vulnerability assessment represents an important milestone in Australia's climate change response. It is the most comprehensive assessment of climate change vulnerability conducted for a tropical marine ecosystem and provides the basis for a continued management response to the implications of climate change for the GBR. As such, it will be an important source document for another major Australian Government initiative that will contribute to future policy responses to climate change – the new *Outlook Report for the Great Barrier Reef Region*. The Outlook Report will provide a regular and reliable means of assessing performance for the long-term protection of the GBR Marine Park. The report will assess the overall condition of the GBR ecosystem, and current and future trends in pressures on the GBR, such as climate change.

24.3.3 Climate change and World Heritage listing

The GBR was listed as a World Heritage Area under the World Heritage Convention in 1981. In 2005, a number of non-government organisations put forward petitions to have four World Heritage properties, including the GBR, included on the World Heritage in Danger List because of the threat of climate change to the World Heritage values. At the World Heritage Committee meeting in 2006, the Committee noted but did not adopt the petitions.

The Committee has so far chosen not to consider the 'in-danger' listing because of climate change but is instead exploring alternative options for addressing this global issue. The Committee has tasked the World Heritage Centre to prepare a policy document exploring issues relating to the Convention and climate change, including alternative mechanisms for 'in-danger' listing.

Australia's efforts to respond to the threat of climate change to the GBR are among the most comprehensive worldwide. Few other World Heritage Areas in the world are doing as much to understand and address the challenges climate change poses. The Australian Government position is that including the GBR on the World Heritage in Danger List will do little to improve the outlook for this World Heritage Area regarding the threat of climate change.

24.3.4 Adapting Great Barrier Reef management

The ability of management to adapt to climate change will be critical to the future of the GBR, and for the social and economic services it provides. While science is providing important insights about the impacts of climate change on ecosystems such as the GBR, effective management strategies in a changing climate are only just emerging. There is now a need to test and refine these ideas, and to accelerate learning through sharing management experiences – successes and failures – in responding to the challenges of climate change. The GBRMPA has a key role to play in this global effort, as it is one of the leaders in adapting natural area management to climate change. However, now more than ever before, management needs to address cumulative impacts and be inclusive, bold and adaptive if it is to be effective in averting the crisis that is currently confronting tropical marine ecosystems.

An overwhelming conclusion of this assessment is that key components of the GBR are highly vulnerable to climate change, and signs of this vulnerability are already evident. The range of possible climate futures makes it clear that further degradation of the ecosystem is unavoidable. Even if the causes of global climate change were addressed today, residual greenhouse gases in the atmosphere will prevent the global climate from stabilising this century. Therefore, some degree of change is inevitable. However, the extent of that change, and the implications for the condition of the GBR, will depend on the rate and magnitude of climate change and the resilience of the ecosystem. Even though preventing damage is no longer an option, it is critical that marine protected area managers focus on opportunities for improving the prognosis of this exceptionally important ecosystem. This assessment provides the foundation for such measures in the GBR.

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