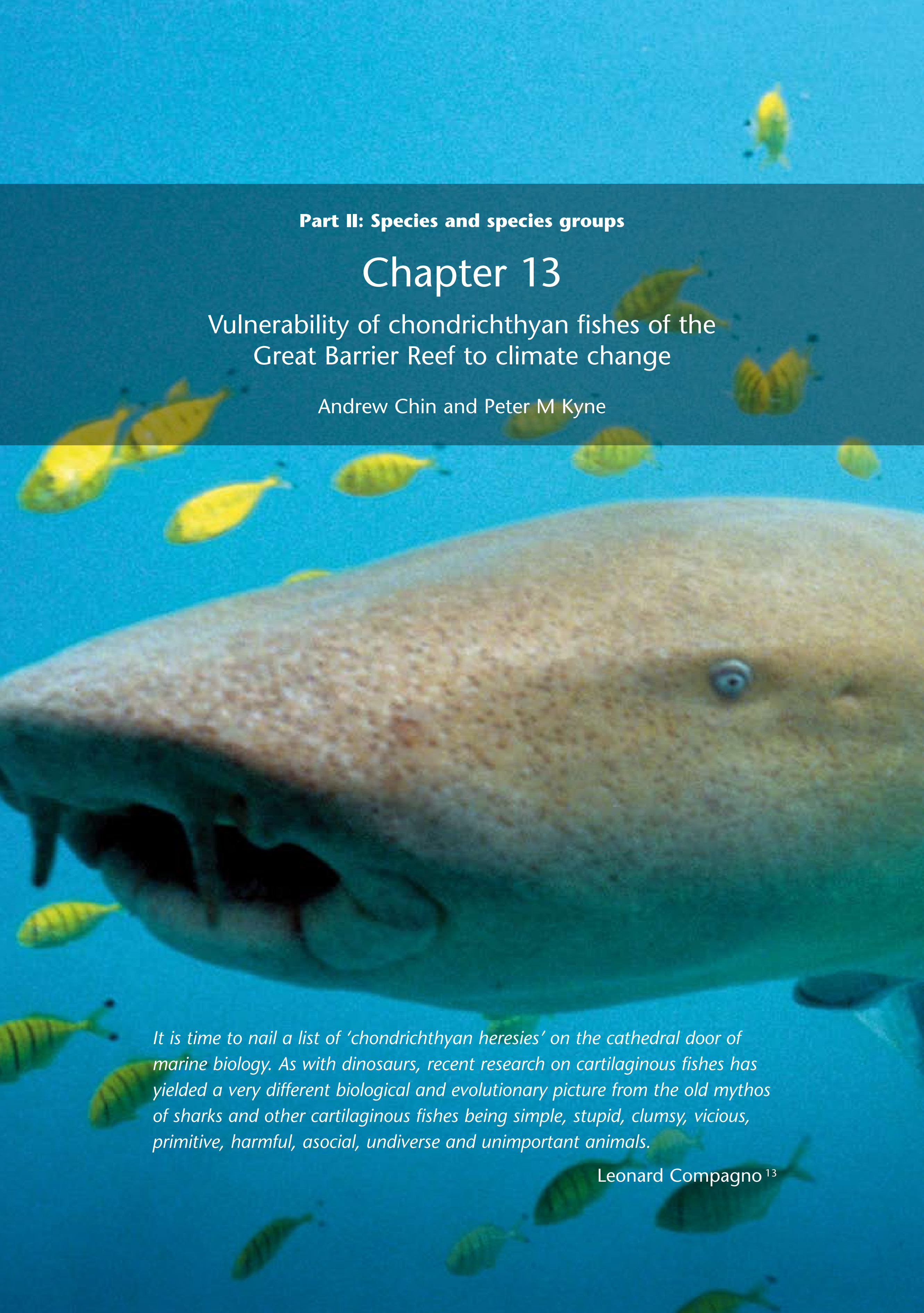


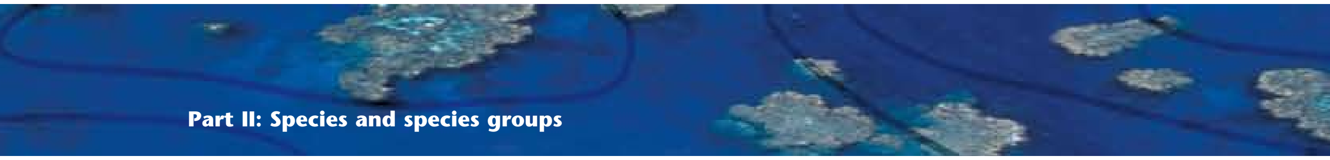
Part II: Species and species groups

Chapter 13

Vulnerability of chondrichthyan fishes of the Great Barrier Reef to climate change

Andrew Chin and Peter M Kyne

> *It is time to nail a list of 'chondrichthyan heresies' on the cathedral door of marine biology. As with dinosaurs, recent research on cartilaginous fishes has yielded a very different biological and evolutionary picture from the old mythos of sharks and other cartilaginous fishes being simple, stupid, clumsy, vicious, primitive, harmful, asocial, undiverse and unimportant animals.*
>
> Leonard Compagno [13]



13.1 Introduction

This chapter addresses the potential impact of climate change on the chondrichthyan fauna of the Great Barrier Reef, that is, the sharks, rays, skates and holocephalans that occur within the Great Barrier Reef region. The terms 'sharks and rays' or 'sharks' are used throughout this chapter to describe this diverse group of fishes.

Relatively little is known about the sharks and rays of the Great Barrier Reef (GBR), and research has been sporadic and patchy. We have collected information from a variety of sources including unpublished data to assemble a baseline of understanding on what climate change may mean for the sharks of the GBR. This assessment provides predictions about how climate change may affect these animals. These predictions rely on information contained in other chapters about climate change and its impacts on the habitats and biological processes of the GBR ecosystem.

We have used a semi-quantitative method to assess the vulnerability of sharks and rays to climate change, and our approach is modelled on methods used to assess the ecological risk of many animals, including sharks and rays, in fisheries. The intent is to use a clear and logical process to assess the vulnerability of the various species and groups of sharks and rays to predicted climate change scenarios over the next 100 years. Whereas this assessment is restricted to the sharks and rays of the Great Barrier Reef, it is hoped that this process will be of use in assessing the potential impacts of climate change on species in other regions.

13.1.1 Chondrichthyan fishes

The chondrichthyan fishes are more commonly known as sharks, rays, skates and holocephalans. These fishes have skeletons made of light and flexible cartilage instead of bone. This separates them from the bony fishes (the teleosts) such as coral trout and salmon.

Sharks and rays have been present in the Earth's oceans for about 400 million years, and in that time have been a highly successful group of vertebrates. Today approximately 1200 species of sharks and rays occur in habitats ranging from tropical coral reefs to Arctic waters, and freshwater rivers to deep sea habitats of the continental slope and beyond[5,14]. Australia has a diverse range of sharks and rays with around 300 species recorded, half of which are found nowhere else in the world[40]. The sharks and rays of the tropical waters of northern Australia have one of the highest levels of diversity and endemism in the world[40,39,48]. The GBR also contains a diverse range of shark and rays with 134 species recorded from the region[35,36,40]. This chapter considers all species found within the GBR, as well as those occurring in adjacent habitats, that is, the deepwater and freshwater environs that are interconnected with the GBR ecosystem. Sharks and rays occur in all GBR habitat types with a handful of species also occupying freshwater habitats on the GBR coast[38].

13.1.1.1 Life history strategies

Sharks have very different life history traits compared with teleost fishes and have evolved K-selected life histories (Figure 13.1). This means that sharks have reproductive strategies geared towards producing a small number of well-developed young that have high survival rates. In this context, shark populations have characteristics similar to marine mammals such as dolphins, and are especially vulnerable to human impacts[5]. Compared to most bony fishes, sharks:

- are relatively slow growing and long-lived
- generally take a long time to reach sexual maturity
- reproduce slowly and produce few young
- have fewer natural enemies and higher survival rates[5,29].

In general, these life history traits mean that adult sharks are relatively hardy (low adult mortality rates), and many sharks are able to tolerate a wide range of environmental conditions. However, the low reproductive rate also means that adaptation through evolutionary change is relatively slow. Present groups of sharks appeared in the Jurassic and Cretaceous periods between 245 and 65 million years ago, and have not undergone significant evolutionary change since.

Figure 13.1 *Compared to bony fish, sharks live for a long time, grow slowly and produce few young. As a group, they have relatively slow rates of evolutionary change and are sensitive to intense human pressures. Once depleted, shark populations can take considerable time to recover.*

This reproductive strategy also makes sharks vulnerable to unnaturally high levels of adult mortality. A K-selected life history strategy means that the number of young produced is closely linked to the number of breeding adults. Thus, as the number of adult sharks declines, the number of new recruits entering the population may also decline. As a result, shark populations can be reduced relatively quickly and once depleted, may take a long time to recover. For example, demographic analyses of sawfish populations in the western Atlantic suggest that even if effective conservation measures are introduced, recovery of these populations could take several decades[64].

13.1.2 Ecology, significance and values of chondrichthyan fishes in the GBR

13.1.2.1 Ecological roles

All sharks are predatory and as a group feed on a wide variety of prey. In general, smaller benthic dwelling sharks may feed primarily on crustaceans, molluscs and other invertebrates, whereas reef sharks and more open water species prey primarily upon fishes. Species such as whale sharks, *Rhincodon typus*, and manta rays, *Manta birostris*, are specialists that feed on plankton[86]. Sharks live in a variety of habitats, ranging from nearshore environs and coral reefs to open water pelagic environments and benthic habitats of the continental shelf, slope and beyond. Many species found in the GBR move between different habitats at various stages of their life cycle, using habitats such as estuaries and seagrass beds as nurseries or foraging grounds[3,26,65,74].

Their wide distribution and consumption of a diverse range of prey mean that sharks perform important roles in the GBR ecosystem[56,61,73]. Many sharks are higher-level predators[86], and ecosystem models suggest that in this role, sharks may help to regulate populations of prey species and maintain ecosystem balance. For example, removing tiger sharks, *Galeocerdo cuvier*, from model simulations caused seabird populations to increase as there were fewer tiger sharks consuming seabirds. This led to increased predation by seabirds on fishes, and ultimately led to the collapse of some fish populations[75]. Research on the diet of tiger sharks suggests that they may play a role in regulating populations of marine turtles and dugongs[66]. Nevertheless, specific 'cause and effect' relationships linking sharks and other marine organisms are difficult to demonstrate. Although it is likely that sharks exert significant influence on other marine organisms, it is difficult to predict what changes might occur should sharks be removed from an ecosystem[75].

13.1.2.2 Ecological groupings

The large number of species of sharks and rays makes it difficult to discuss their ecology on a species by species basis. However, this discussion can be greatly simplified by organising the species into discrete groups based on habitat use, anatomy, ecology and lifestyle. While these sorts of groupings can be developed in a number of ways[13], habitat use is usually a key factor in defining these groups.

This chapter divides the GBR's 134 species of sharks and rays into six discrete units called functional groups. Each functional group is based on the different habitat zones found between the coast and the deep waters of the continental slope. Each habitat zone consists of a number of specific habitats (eg seagrass beds). A species is included in a functional group if it *primarily* occurs in the habitats found in that zone, and is affected or dependent in some way upon the physical, chemical and ecological processes occurring in those habitats. Species lists for each functional group were developed directly from published information on species distribution and habitat use[35,36,40], unpublished data provided by contributing authors (Terence I Walker, Rory B. McAuley, John D Stevens, Christine L Dudgeon and Richard D Pillans) and others (W White pers comm), or inferred from published literature on the same or similar species from other regions. The six functional groups are described below.

- **Freshwater and estuarine** (4 species) – Habitats include rivers and streams, inter-tidal zones of estuaries and bays, mangroves and salt marsh, intertidal seagrass beds, foreshores and mudflats.
- **Coastal and inshore** (47 species) – Habitats extending from coastal sub-tidal habitats to the mid-shelf platform or ribbon reefs. Includes estuaries and bays, sub-tidal seagrass beds, inshore fringing reefs, shallow coastal waters, rocky shoals, sponge gardens and other benthic habitats of the GBR lagoon to 30 metres depth.
- **Reef** (19 species) – Habitats on and immediately adjacent to mid-shelf and outer-shelf coral reefs, down to a maximum depth of 40 metres in the GBR lagoon and to 60 metres on outer shelf reefs.
- **Shelf** (26 species) – Deeper water and seabed habitats between the mid-shelf and outer reefs, extending to the continental slope edge. Includes waters from the surface to 200 metres (approximately the shelf edge) and benthic habitats such as deepwater seagrass beds and *Halimeda* mounds, rocky shoals and sponge gardens (40 to 60 metres depth).

- **Bathyal** (54 species) – Benthic habitats of the continental slope and beyond, extending down to 2000 metres depth.
- **Pelagic** (10 species) – Open ocean waters extending from the edge of the outer reefs and beyond into the Coral Sea.

Highly mobile and ecologically 'flexible' species such as the bull shark, *Carcharhinus leucas*, commonly occur in more than one habitat type and thus appear in more than one functional group. In contrast, more sedentary and less 'flexible' species such as the freshwater sawfish *Pristis microdon* are restricted to particular habitats and are only listed in one functional group.

Functional groups are generalisations and while there may be overlap between groups, they have been developed to provide a manageable framework for assessing the vulnerability of GBR sharks and rays to climate change.

13.1.2.3 Social, cultural and economic significance

The sharks and rays of the GBR have significant social, cultural and economic values. Sharks and rays are of great social and cultural importance to indigenous communities of the GBR coast and Torres Strait. Several indigenous groups consider sharks as cultural icons and totems, and sharks and rays are pivotal characters in many dreamtime stories. The act of fishing is an important social activity and rays are an important source of food for many indigenous communities[12,43,68].

Sharks and rays are also valuable as dive attractions in the A$6.1 billion GBR tourism industry. Surveys of SCUBA divers visiting the GBR found that sharks were rated as the top attraction that divers most wanted, and most expected, to see[45]. The economic value of sharks as living attractions has been documented outside Australia. Research in the Maldives found that a single grey reef shark, *Carcharhinus amblyrhynchos*, generated US$33,500 per year at the most popular shark watching dive site, and was worth on average US$3,300 per year across all shark watching dive sites. In the Caribbean, the tourism value of a single live Caribbean reef shark, *Carcharhinus perezi*, has been estimated at between US$13,300 and US$40,000 per year[1]. The income generated by shark ecotourism has prompted increased awareness and community education about shark conservation, and provides economic benefits for both the tourism industry and local communities[1].

Sharks are also taken as target species and bycatch in the Queensland East Coast Inshore Finfish Fishery[58,63]. The pressure on sharks in the GBR has increased since 1990, with more specialist shark fishers entering the gillnet fishery and more effort being directed at targeting sharks[59]. Commercial fishery logbooks have recorded a significant increase in reported shark catch and effort in the net fishery in the GBR, rising from 295 tonnes from 191 boats in 1994 and peaking at 1202 tonnes from 221 boats in 2003[53]. Estimates of targeted shark fishing effort (as the percentage of fishing days targeting shark) increased by 28 percent over the same period meaning that fishers have shifted effort to target sharks[59]. The total Gross Value of Production derived from sharks taken from the GBR net fishery has risen accordingly, from A$1.97 million in 1988, peaking at A$7.21 million in 2003[53]. Since 2003, both the number of boats and catch have declined with 150 boats landing 634 tonnes in 2005. This follows the buyout of 59 active net licenses under a structural adjustment package following rezoning of the Great Barrier Reef Marine Park[53,54]. However, there are still significant concerns regarding the fishery, including the long-term sustainability of the take of sharks and rays[16].

13.1.3 Status of chondrichthyan fishes in the Great Barrier Reef

There is little information available about the status and trends of shark populations on the GBR[10]. The most extensive set of data are contained in catch records reported in commercial fisheries logbooks. However, logbooks only record the combined catch of all shark and ray species and thus cannot be used to assess the status and trends of individual species. Long-term fishery-independent surveys of shark populations on the GBR have not been conducted. Smaller-scale research surveys are ongoing, but at this time, they are limited in duration and coverage.

There are conservation concerns for several species of sharks and rays in the GBR and 19 species are listed as threatened (Critically Endangered, Endangered or Vulnerable) by the International Union for Conservation of Nature and Natural Resources in the 2006 *IUCN Red List of Threatened Species*[33]. The grey nurse shark, *Carcharias taurus*, Bizant river shark, *Glyphis* sp. A and all four species of sawfish occurring in the GBR region are listed as Critically Endangered. Additionally, recent research has revealed significant declines in populations of whitetip reef shark, *Triaenodon obesus*, and grey reef shark, *Carcharinus amblyrhynchos*, on the GBR[57]. Formal assessment of the conservation status of these species in the GBR using the IUCN Red List Categories and Criteria is underway and will likely reveal conservation concern for these reef sharks (W Robbins pers comm).

The conservation status of sharks on the GBR is of concern to marine managers due to increases in reported catch and the general lack of information available on population trends[10]. This is especially relevant given the inherent vulnerability of sharks and rays to fishing pressure and the poor sustainability record and documented collapse of many shark fisheries around the world[4,82].

13.1.4 Climate change factors affecting chondrichthyan fishes

Sharks and rays may be affected by a large number of physical, chemical and ecological factors that influence their immediate environment or affect the habitats, food webs and ecological interactions upon which they depend. Consequently, the climate change scenarios and ecological processes described in other chapters of this volume form the basis of our understanding of how climate change may affect sharks and rays. Relevant chapters include those on species groups (marine microbes, plankton, mangroves, seagrass, corals, benthic invertebrates and fishes), and habitats and processes (reefs, pelagic, coastal and estuarine, physical oceanography and coral reef resilience).

A review of this information revealed that there are ten climate change drivers most likely to affect sharks and rays. These drivers may alter environmental conditions resulting in direct physiological effects, or may affect habitats and ecological processes that indirectly affect sharks and rays. The assessment considers changes and impacts predicted over the next 100 years.

Direct links between climate drivers and GBR sharks and rays

Three climate change drivers were identified as *directly* affecting the physiology of sharks and rays.

13.1.4.1 Sea and air temperature

Projected increase in sea temperature of 1 to 3°C, projected increase in air temperature of 4 to 5°C by 2100

The majority of GBR sharks and rays are ectothermic and changes in environmental temperature will affect physiological processes such as metabolic rates[7]. Most ectothermic fishes favour habitats that have a suitable temperature range. Temperature may also influence behaviour, and tracking studies have shown that sharks will feed in warmer waters and rest in cooler waters[42]. Changes in temperature driven by climate change may result in changes in metabolism, behaviour and movement patterns. Sharks may move to new areas where optimum temperatures exist (see section 13.1.6), however, research into thermal tolerances for some estuarine and benthic species has indicated that they can tolerate a wide range of temperatures[18,30,81]. Predicted increases in temperature of 1 to 3°C may be greater in shallow freshwater, estuarine, coastal and inshore habitats and reef flat lagoons during low tide, than in the shelf, bathyal and pelagic environments.

Increased temperature will also result in lower dissolved oxygen concentrations in the water. This could increase the possibility of respiratory stress as rising temperature results in decreased dissolved oxygen levels and increased metabolic rates. However, at least one species of shark (epaulette shark, *Hemiscyllium ocellatum*) has demonstrated the ability to tolerate these conditions[72], and some species show reduced activity and metabolic rates in response to lower oxygen levels[7]. Consequently some sharks may be able to tolerate lower levels of dissolved oxygen.

There is little evidence that the occurrence or severity of disease in sharks has changed due to anthropogenic factors including climate change[37]. However, future increases in temperature may increase the incidence of disease by facilitating the spread of warm-water parasites and increasing their growth rates and reproductive output[37].

13.1.4.2 Ocean acidification

pH decrease of 0.4 to 0.5 by 2100

The acid/base (pH) balance in sharks and rays is tightly regulated and they can compensate for acidity changes by rapid pH buffering[17]. The gills are the main organ that balances pH in sharks and rays. Sharks and rays are found in a wide range of environments and pH regimes, but the effects of environmental pH on the physiology and behaviour are not well understood. Increased ocean acidity could lead to increased energy costs as sharks and rays work harder to maintain an optimum pH balance.

13.1.4.3 Freshwater input

Increased salinity extremes due to greater rainfall variability (more intense droughts and floods)

During the tropical monsoon, the GBR receives pulses or flushes of fresh water from floods created by heavy rain in coastal catchments. Climate change may increase rainfall variability, resulting in greater extremes of flood and drought. Prolonged droughts with reduced freshwater inputs may increase salinity in some intertidal and sub-tidal environments, especially in closed or impounded waters, and cause freshwater ponds to dry up. Increased temperature and evaporation may further increase salinity extremes, and reduce dissolved oxygen levels (see section 13.1.4.1). Floods will reduce salinity and may wash pollutants from the catchment into coastal habitats. The greatest changes in salinity are likely to occur in freshwater, estuarine and coastal habitats.

Some sharks and rays can tolerate a wide range of salinity regimes and may even be predominantly found in freshwater environments[7,38]. Experiments show that some sharks and rays can tolerate decreased salinity, but that this may result in increased energy costs to maintain the correct osmotic balance[7]. Similarly, some sharks and rays can tolerate increases in salinity by retaining more salts such as urea in their blood[51,79]. However, the impacts of long-term salinity changes on sharks and rays are not well understood.

Indirect links between climate drivers and GBR sharks and rays

Seven climate change drivers were identified as *indirectly* affecting sharks and rays in the GBR. These large-scale drivers affect the condition and availability of critical habitats, or may alter ecological processes that regulate the abundance and distribution of prey.

Some sharks use particular habitat types such as shallow seagrass meadows or estuarine habitats for nursery grounds where young can find food and seek shelter from predators. Adult sharks may use certain habitat types to find food and shelter, to mate or give birth. There is also increasing evidence of philopatry that may strengthen the reliance of some sharks on particular habitats and locations[31].

Some species (eg the whale shark) rely on certain prey while others are able to exploit a wide range of prey species. The movement of highly migratory, plankton feeding species such as whale sharks have been correlated with the availability of plankton (see section 13.1.6). Pelagic species may rely on a biological calendar; events such as turtle nesting, seabird fledging or aggregations of prey such as baitfish shoals to influence their movements.

13.1.4.4 Oceanographic impacts

Changes in East Australian Current bifurcation point, currents and upwellings linked to the El Niño Southern Oscillation

The East Australian Current (EAC) is the main current affecting the GBR, but the reefs and island chains create local eddies and jets. Climate change could cause the bifurcation point of the EAC to move south (Steinberg chapter 3). Increased current strength may lower thermoclines and reduce the strength of upwelling currents. Upwellings of nutrient rich cooler water occur off outer shelf reefs, for example around the Swains Reefs. The input of nutrients allows for the growth of plankton and thus, forms the basis of marine food webs in these areas.

Climatic changes expressed through changes in El Niño events can alter these currents and upwellings and thus, alter prey availability, migration patterns and the timing of specific events such as baitfish aggregations or plankton blooms. Migration patterns of whale sharks in Western Australia have been linked to plankton blooms and currents associated with El Niño[80,87]. In addition, El Niño and upwellings have been linked to significant changes in prey availability that caused collapses in fisheries and seabird populations (Kingsford and Welch chapter 18, Congdon et al. chapter 14).

13.1.4.5 Water and air temperature

Projected increase in water temperature of 1 to 3°C, projected increase in air temperature of 4 to 5°C by 2100

Increased temperature will increase the frequency and severity of coral bleaching events, and potentially increase bio-erosion. This could lead to long-term losses of coral habitats, particularly of corals such as *Acropora* that create the complex structure of the coral reef that provides habitat for many reef

fishes. Up to half of the species of reef fish, important prey for some sharks and rays, could decline if coral cover is decreased (Munday et al. chapter 12). Increased temperature would also increase the incidence of seagrass 'burning' leading to habitat loss for both sharks and their prey. Losses would be greater in coastal and shallow reef seagrass habitats (Waycott et al. chapter 8). Temperature can affect nutrient cycling in microbial communities and plankton with flow-on effects to marine food webs (Webster and Hill chapter 5, McKinnon et al. chapter 6).

13.1.4.6 Sea level rise

Sea level rise of 0.1 to 0.9 metres by 2100

Increasing sea level will have significant effects on coastal habitats. Rising sea level will increase salinity in estuaries and the lower reaches of creeks and rivers, and alter geophysical processes of erosion and deposition along the coastal zone. Mangroves may decline in some areas but expand in regions such as the Fitzroy Basin by replacing salt marsh and freshwater wetland habitats. However, physical barriers such as human structures may prevent migration landward. The loss of salt marshes and wetlands could have significant effects on prey species. Sea level rise would also drive seagrasses landward and lead to expansion in some areas, but again physical barriers and mangroves could restrict migration landward. In other areas, seagrasses could become 'squeezed' between deeper water and barriers (such as established mangrove forests) and decline. Impacts on rivers, wetlands, mangroves, salt marshes, seagrasses, estuaries, mudflats and beaches will alter the availability of these habitats to sharks and rays, and any prey that also rely on these habitats[11] (Waycott et al. chapter 8, Lovelock and Ellison chapter 9, Sheaves et al. chapter 19).

13.1.4.7 Severe weather

Increased frequency and intensity of severe storms and cyclones

Increases in destructive storms and cyclones will have significant impacts on immobile organisms and habitats, especially in shallow waters. Storms can generate destructive winds and waves that physically damage habitats, or lead to erosion and deposition of large amounts of material that alter hydrology and the physical landscape. More intensive storms result in increased levels of damage, and increased frequency of storms means that habitats and communities have less time to recover between storm events. Habitat loss will occur when the frequency and intensity of severe weather events exceeds the habitat's ability to recover from one event to the next. Habitats most at risk from severe weather include shallow habitats such as wetlands, mangroves, seagrasses and coral reefs. Many sharks and rays, and/or their prey, rely on these habitats for shelter or food. Seagrass and mangrove habitats are also critical nursery grounds for a number of species and loss of these habitats could have significant impacts on population growth and recovery of prey. Severe storms may also affect the movement and behaviour of some sharks[28].

13.1.4.8 Freshwater input

Increased variability in rainfall regimes leading to greater extremes of droughts and floods

Increased extremes of drought and flood can result in increased extremes of salinity that lead to stress in marine communities such as seagrass beds and coral reefs. Floods and associated decreased salinity have resulted in significant loss of seagrasses (Hervey Bay) and coral reefs (Keppel Islands) in the past. Increased flood activity may increase the amount of pollutants reaching coastal habitats and mid-shelf reefs. Severe droughts will reduce freshwater input into catchments and reduce the availability of freshwater habitats. Prolonged droughts can make plant communities more vulnerable to diseases and pests, lead to mortality and cause long-term changes in community composition. Wetlands, mangroves, seagrasses and coral reefs are important habitats to sharks and rays and their prey.

The productivity of freshwater, estuarine, coastal and inshore systems may be closely linked to rainfall, with higher rainfall triggering increased abundance of prawns and crabs, and influencing the reproduction of fishes such as barramundi[11,44,46,70]. Increased variability in rainfall and freshwater input may decrease the stability of coastal food webs and cause greater extremes of prey availability (Kingsford and Welch chapter 18, Sheaves et al. chapter 19).

13.1.4.9 Light and ultra-violet radiation

Increased levels of light and ultra-violet (UV) radiation linked to El Niño events

During El Niño events, cloud cover and wave action are reduced which allows greater penetration of ultraviolet (UV) radiation through the water column. Increased levels of UV radiation may alter the community composition of microbial communities with effects on nutrient cycling and productivity of key habitats. Higher levels of UV radiation have detrimental effects on some larval fish. Increased light intensity may damage some seagrasses and is an important contributing factor in coral bleaching. It is not known how much climate change will affect light and UV radiation levels and subsequently impact GBR inhabitants (Waycott et al. chapter 8, Hoegh-Guldberg et al. chapter 10, Munday et al. chapter 12, Fabricius et al. chapter 17).

13.1.4.10 Ocean acidification

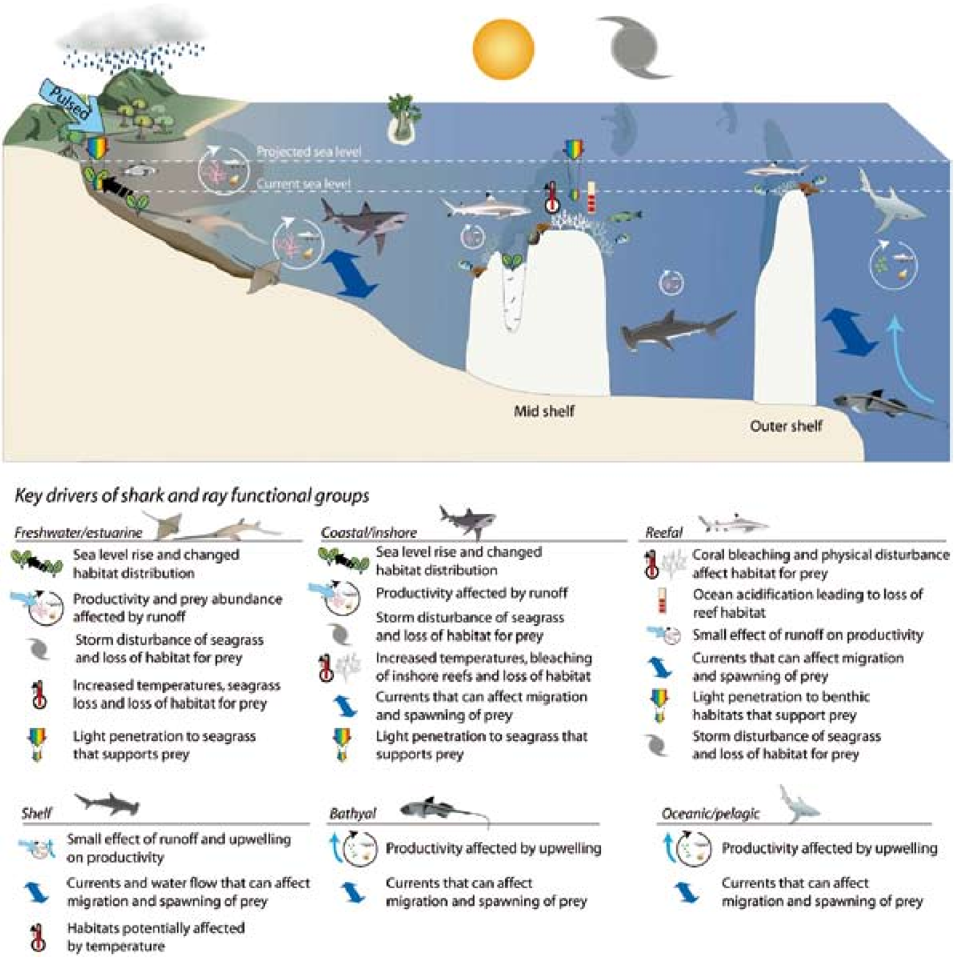
pH decrease of 0.4 to 0.5 by 2100

Ocean acidification has been included as a large-scale driver for the reef functional group only. The potential effects of ocean acidification on coral reefs have been explored and literature suggests that increased acidity predicted by climate change scenarios could lead to significant degradation of coral habitats (Hoegh-Guldberg et al. chapter 10). While increased ocean acidification may reduce skeletal development in some marine organisms, the effects of ocean acidification on sharks and rays, or on the vast majority of habitats and ecological processes in the GBR are not well understood. Ocean acidification has not been considered in the assessment of the other five shark and ray functional groups.

13.1.5 Climate change drivers and functional groups

Sharks and rays of the GBR depend upon a variety of habitats and ecological processes, and these dependencies differ according to the functional group. For example, the health of seagrass beds may have a significant effect on sharks in the coastal and inshore functional group, whereas sharks in the pelagic functional group are more dependent on currents and upwellings. The habitats, key processes and dependencies of each functional group, and the interaction of climate change drivers with these processes, are summarised in Figure 13.2.

Figure 13.2 *Six functional groups of sharks and rays and the main climate change drivers that may affect the habitats and biological processes upon which they depend*



Key drivers of shark and ray functional groups

Freshwater/estuarine
- Sea level rise and changed habitat distribution
- Productivity and prey abundance affected by runoff
- Storm disturbance of seagrass and loss of habitat for prey
- Increased temperatures, seagrass loss and loss of habitat for prey
- Light penetration to seagrass that supports prey

Coastal/inshore
- Sea level rise and changed habitat distribution
- Productivity affected by runoff
- Storm disturbance of seagrass and loss of habitat for prey
- Increased temperatures, bleaching of inshore reefs and loss of habitat
- Currents that can affect migration and spawning of prey
- Light penetration to seagrass that supports prey

Reefal
- Coral bleaching and physical disturbance affect habitat for prey
- Ocean acidification leading to loss of reef habitat
- Small effect of runoff on productivity
- Currents that can affect migration and spawning of prey
- Light penetration to benthic habitats that support prey
- Storm disturbance of seagrass and loss of habitat for prey

Shelf
- Small effect of runoff and upwelling on productivity
- Currents and water flow that can affect migration and spawning of prey
- Habitats potentially affected by temperature

Bathyal
- Productivity affected by upwelling
- Currents that can affect migration and spawning of prey

Oceanic/pelagic
- Productivity affected by upwelling
- Currents that can affect migration and spawning of prey

13.1.6 Documented impacts of climate change on sharks and rays in the GBR and elsewhere

There are no published assessments on the impacts of climate change on any of the sharks and rays found in the GBR. Indeed, there is little information available on the topic anywhere in the world. However, there has been considerable focus on the effects of climate warming on marine communities in the north Atlantic[60,69] and a handful of studies have included references to chondrichthyan species[50,52,71]. Alterations in community structure, together with biogeographical shifts of calanoid copepods and fish communities in the northeast Atlantic has been correlated with increasing northern hemisphere temperature and the North Atlantic Oscillation[2,50,52].

In the northeast Atlantic, increasing water temperature has been advantageous to subtropical fish species that have wide latitudinal ranges, while the abundance of temperate and more narrow-ranging species have decreased[52], with many species displaying shifts in mean latitude or depth over extended time periods[50]. In the Bay of Biscay, numbers of the temperate spiny dogfish, *Squalus acanthias*, declined from 1973 to 2002, which Poulard and Blanchard[52] related to climate change. They also documented changes in the abundance of the cuckoo ray, *Leucoraja naevus*. However, it may be more difficult to isolate the effects of ocean warming from those of historically high fishing pressure (targeted and bycatch) on both of these species in the northeast Atlantic. Perry et al.[50] did however, show latitudinal and depth shifts in both exploited and non-exploited marine fish species. They demonstrated a shift in mean depth for the cuckoo ray related to temperature, with the species moving into deeper water as a response to ocean warming. Three chondrichthyan species examined (cuckoo ray, spiny dogfish and the small spotted catshark, *Scyliorhinus canicula*) did not display latitudinal shifts related to climate warming[50].

Quero[55] reported on the northward extension of the distributions of tropical fish species, and Stebbing et al.[71] linked warming of the North Atlantic with the immigration of warmer-water species to the Cornish coast of England. For the period of 1960 to 2001, the increasing number of records of southern species was significantly correlated with rises in temperature[71]. The analysis included the first record of the sharpnose sevengill shark, *Heptranchias perlo*, for the British Isles and the first record of the tropical to warm-temperate bigeye thresher, *Alopias superciliosus*, for Cornwall.

It has been theorised that some pelagic shark species may be detrimentally affected by climate change due to the role temperature plays in determining seasonal distribution and abundance. Seasonal aggregations of whale sharks off Western Australia have been weakly correlated to sea surface temperature and this parameter has been shown to be highly correlated with the abundance of basking sharks, *Cetorhinus maximus*, off southwest Britain[15,87]. Whale sharks are known to aggregate at certain times to feed on plankton blooms associated with coral spawning[80]. The loss of coral reefs or disruption of coral spawning could have significant impacts on these animals. Stewart and Wilson[77] suggested that coral bleaching events, which are related to increasing water temperatures, and rapid climate change are amongst the greatest threats to whale sharks.

13.2 Vulnerability of GBR sharks and rays to climate change

A standardised framework for assessing the vulnerability of habitats, taxa and ecological processes to climate change was described in chapter 1. This framework uses three ‘components’, *exposure*, *sensitivity* and *adaptive capacity* to derive vulnerability to climate change drivers. Exposure and sensitivity are ‘negative’ components that describe the potential impacts of climate change. The higher the exposure or sensitivity, the greater the vulnerability to climate change. Adaptive capacity is a ‘positive’ component that describes an organism or habitat’s ability to accommodate change. A high adaptive capacity will reduce vulnerability to climate change. This chapter assesses these three components and integrates them using an approach used in fisheries ecological risk assessments (see section 13.2.4).

The method used to assess vulnerability to climate change is intended to be clear and logical, and follows a progression of clearly defined steps:

1. Ranking the exposure (low, moderate, high) of each functional group to the ten climate change drivers identified
2. Identifying the biological *attributes* of sharks and rays that direct their response to climate change drivers. These attributes define their sensitivity and adaptive capacity
3. Ranking each attribute of sensitivity and adaptive capacity as low, moderate or high, for each species to each of the climate change drivers
4. Multiplying the rankings for exposure, sensitivity and adaptive capacity to derive a vulnerability assessment for each species in each functional group
5. Collating the individual species rankings into an overall assessment of the vulnerability of each functional group

13.2.1 Exposure

Exposure is a 'negative' component with high exposure equating to increased potential impact from climate change. Ten of the climate change drivers identified in chapter 2 were identified as being relevant to sharks and rays of the GBR. These drivers may affect the physiology of sharks and rays by altering the immediate physical and chemical environment, or affect the large-scale ecosystem processes (eg habitat quality or abundance of prey) upon which sharks depend. Physiological drivers exert direct pressure on sharks, whereas large-scale processes affect other parts of the ecosystem that in turn have indirect flow-on effects on sharks.

Exposure to a specific climate change driver depends on two factors:

- the extent to which the species' geographic and depth range overlaps with the climate change driver; and,
- the extent to which the climate change driver effects the habitats and ecological processes upon which the species depend.

To identify the key processes and habitats likely to be affected by the ten climate change drivers published literature, chapter 2 and the other chapters in this volume were used. This list was compared with the functional group descriptions to rank exposure (low, moderate or high) of each group. For example, if the majority of habitat types in a functional group were highly likely to be severely affected by sea level rise, the functional group would be assessed as having high exposure to that climate change driver.

13.2.2 Sensitivity

Sensitivity is a 'negative' component where high sensitivity equates to increased potential impact from climate change. The sensitivity of a species to a climate change driver depends on its ability to resist or adapt to change. However, attributes that define sensitivity can also be considered as factors that provide a species with the ability to adapt to change – adaptive capacity. For example, sensitivity to increasing temperature can also be defined as a species' capacity to adapt to warmer conditions. Consequently, this chapter treats sensitivity as attributes of a species that it cannot easily change, whereas attributes linked to its ability to change or adapt are considered as attributes of adaptive capacity. Sensitivity is defined by two attributes:

- *Rarity:* A rare species has a small population and may lack genetic variation. Smaller populations are more sensitive to pressures as they have fewer individuals or 'chances' to cope with climate change drivers. Secondly, their lower abundance means a lower net reproductive output. This reduces the species' ability to recover from climate change related mortality. This is especially important in sharks and rays that, as a group, have conservative life history characteristics. Rare species have high sensitivity.
- *Habitat specificity:* Some sharks and rays may be restricted to a particular habitat as these provide the species with necessary resources such as suitable prey or refuge from predators. These species may not be able to compete effectively in other habitats whereas more flexible species are able to exploit alternative habitats should one habitat type be adversely affected. Species with high habitat specificity have high sensitivity.

Sensitivity to each climate change driver was ranked as low, moderate or high. This ranking was based on literature and unpublished data about the rarity and habitat use of these species.

13.2.3 Adaptive capacity

Adaptive capacity is a 'positive' component that describes a species' ability to acclimate or accommodate change. High adaptive capacity means that a species is able to more readily accommodate change, which reduces the potential impacts from climate change drivers. Accommodation may occur where physiological or behavioural responses result in acclimation or compensation that allow the species to be successful in the new conditions. This is the opposite of the other two components of vulnerability (exposure and sensitivity), which are 'negative' components and the higher they are, the greater the potential impact.

In order to integrate the three components (exposure, sensitivity and adaptive capacity) in the assessment framework all three components need to be expressed as 'negative' terms. Hence, the attributes of adaptive capacity need to be expressed as levels of *inadaptability*. For example, if a species has physiological traits that allow it to tolerate a wide range of temperatures, it is ranked as having *low* inadaptability, which is the equivalent of saying that it has a *high* adaptive capacity.

Inadaptability is defined by four attributes:

- *Trophic specificity:* species that depend on specific types of prey are less adaptable. If certain types of prey become unavailable, these sharks and rays may not be able to exploit alternative prey types. Such species have high inadaptability. An example would be the whale shark that feeds exclusively on plankton. Species that feed on a wide range of prey items may shift feeding patterns to exploit alternative prey. These species have a low inadaptability. For example, tiger sharks feed on a larger variety of prey and are better able to switch feeding preferences.
- *Physical or chemical intolerance:* some species have physiological traits that allow them to tolerate a wide range of physical and chemical conditions such as salinity or temperature. These species are better able to accommodate changing conditions. For example, the bull shark can tolerate a wide range of salinities and would be ranked as having low inadaptability.
- *Immobility:* some sharks and rays have the ability to move between different areas to exploit favourable conditions[30]. Immobile species are incapable of travelling large distances

(morphological restrictions) or cannot overcome physical barriers that prevent them from reaching new areas. For example, a species living on isolated seamounts is 'immobile' if it cannot reach another seamount. This species would be assessed as having high inadaptability.

- *Latitudinal range (proxy for temperature intolerance):* some species of sharks and rays are found over large latitudinal ranges and thus inhabit a wide range of temperature regimes. This infers that these species have the capacity to be successful in a wide range of temperatures. This attribute is particularly important, as there is little information available on the temperature tolerances of the vast majority of sharks and rays found in the GBR.

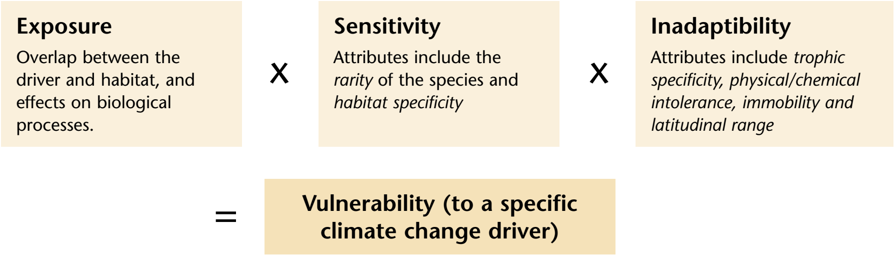
The inadaptability of each species was ranked as low, moderate or high. This ranking was based on literature and unpublished data on these species.

13.2.4 Assessing the vulnerability of shark and ray species

Chapter 1 provides a framework for assessing vulnerability that combines the three components exposure, sensitivity and adaptive capacity. In this chapter, the framework has been adapted to risk assessment techniques developed for sharks and rays in Australian fisheries that provide semi-quantitative assessments[23,78,84,85]. Fisheries ecological risk assessment frameworks use terms such as *availability, encounterability* and *selectivity,* that relate to exposure, and the term *post-release mortality* that relates to sensitivity. This semi-quantitative approach has the advantage that each component is clearly defined and rated using a standard assessment, and that the overall assessment is transparent. If required, interested parties can identify the individual attributes of a species that have resulted in it being assigned a specific vulnerability ranking.

The fisheries risk assessment multiplies the individual component ratings together to produce a final outcome that describes the risk to that species. This chapter uses the same approach as the fisheries risk assessment[85], where each component is individually rated and then multiplied to derive overall vulnerability. The level of exposure, sensitivity or inadaptability is rated as 0.33 (low), 0.66 (moderate) or 1.00 (high). These ratings are multiplied together to derive vulnerability that is expressed as a proportion ranging from 0.00 to 1.00, where 0.00 to 0.33 equals low vulnerability, 0.34 to 0.66 equates to moderate vulnerability, and 0.67 to 1.00 equates to high vulnerability. This is demonstrated in the equation in Figure 13.3.

Figure 13.3 *Integration of the three components of climate change to calculate vulnerability*



Exposure
Overlap between the driver and habitat, and effects on biological processes.

X

Sensitivity
Attributes include the *rarity* of the species and *habitat specificity*

X

Inadaptibility
Attributes include *trophic specificity, physical/chemical intolerance, immobility and latitudinal range*

=

Vulnerability (to a specific climate change driver)

The multiplicative approach is generally conservative and most calculations will result in scores of less than 0.33 (Table 13.1). For example, if a species has high sensitivity and high inadaptability to a climate change driver but is unlikely to ever encounter the driver (low exposure), then overall vulnerability to that driver is low. In contrast, a species will only be assessed as being highly vulnerable when all three components of vulnerability are high (Table 13.1). This is logical because for a species to be highly vulnerable to climate change, it has to be highly exposed *and* have high sensitivity *and* be highly inadaptable. For example, a highly sensitive species that was highly exposed to a climate change driver may not be especially vulnerable *if* it had the ability to rapidly adapt to the change and continue to be successful (low inadaptability).

This framework applies several assumptions and logical rules:

- It is assumed that all climate change drivers, attributes and components of vulnerability are equally significant. For example, temperature has the same significance as severe weather, rarity is as significant as habitat specificity or exposure is as significant as sensitivity.
- When assessing a species' sensitivity or inadaptability, the highest ranking of any of the attributes is used. For example, if a species is very abundant (low rarity = low sensitivity) but is restricted to a single specific habitat type (high habitat specificity = high sensitivity), overall sensitivity is ranked as high. In this case, it doesn't matter how many individuals there are because if that habitat is lost, the impact on all individuals of the species will be high.
- A mathematical consequence of this approach is that when exposure, sensitivity and inadaptability are all moderate, the calculated vulnerability is low (0.66 X 0.66 X 0.66 = 0.29 = low). In this situation vulnerability is arbitrarily assessed as moderate.
- If there is no information available to assess the sensitivity or inadaptability of an attribute, it is ranked as high. This applies the precautionary principle where the lack of information increases risk. This is especially relevant to sharks and rays given their conservative life history characteristics.

Table 13.1 *Calculated outcomes of combinations of vulnerability ratings*

	Sensitivity x inadaptability					
Exposure	L*L	L*M	L*H	M*M	M*H	H*H
H	0.11	0.22	0.33	0.44	0.66	1.00
M	0.07	0.14	0.22	0.29#	0.44	0.66
L	0.03	0.07	0.11	0.14	0.22	0.33

this is ranked as moderate following logical rules (see above)

It should be noted that vulnerability rankings are specific for the GBR region. For example, a temperate species may occur in a wide range of latitudes that extends north into the GBR. Warming in the GBR could alter the range of this species southwards and out of the GBR region. In this scenario, vulnerability would be assessed as high as the species would be 'lost' from the GBR ecosystem, even though it continued to occur in regions south of the GBR.

Many sharks and rays are able to move considerable distances compared with other species. High mobility imparts an additional complication in this assessment and while mobility is assessed as an

attribute of ‘adaptive capacity’, little is known about the capacity to migrate or the present movement patterns of GBR sharks and rays, or indeed how some species might alter their behavioural patterns or habitat use in response to climate change.

13.2.5 Vulnerability assessment results

13.2.5.1 Significance of the ten climate change drivers to sharks and rays

- The most significant climate change driver is temperature as all functional groups have either high or moderate exposure to the direct and/or indirect impacts of increasing temperature.
- Freshwater input and/or ocean circulation are significant drivers for most functional groups. These drivers affect ecosystem productivity and could result in changes to prey availability. Freshwater input affects functional groups closer to the coast while ocean circulation affects the bathyal and pelagic functional groups.
- Sea level rise and severe weather are significant drivers for the freshwater and estuarine, and coastal and inshore functional groups. Rising sea level may result in significant losses of critical estuarine, mangrove and seagrass habitats, and the ecosystem services they provide.
- Exposure to the direct affects of ocean acidification was assessed as low for every functional group. Consequently, every species was assessed as having low vulnerability to direct physiological effects from ocean acidification. Ocean acidification as an indirect, large-scale driver was only assessed for the reef functional group, which had high exposure to this driver.

13.2.5.2 Exposure of each functional group to climate change drivers

Exposure rankings for each functional group are given in Table 13.2. Exposure to each climate change driver varied in response to the habitats and key dependencies and linkages of each group (see Figure 13.2 for review).

- Species in the freshwater and estuarine functional group have the highest exposure of all functional groups, with high exposure to seven of the nine relevant climate change drivers. There are clear links between climate change drivers and most of the key habitats and ecological processes upon which these species depend.
- Species in the coastal and inshore functional group have high exposure to climate change drivers. Many of the habitats and ecological processes that these species depend on are likely to be affected by climate change.
- Species in the reef functional group have high to moderate exposure to climate change drivers. Exposure is through potential declines and loss of coral reefs via increased stresses such as coral bleaching. Ocean acidification has particular implications for coral reefs and was considered in the assessment of the reef functional group.
- Species in the shelf and pelagic functional groups have low to moderate exposure. Few of the climate change drivers are likely to affect habitats and ecological processes that these species depend on.
- Species in the bathyal functional group had the lowest exposure. Most climate change drivers are unlikely to affect these deepwater habitats.

Table 13.2 *Exposure of each functional group to the physiological (direct) and large-scale (indirect) climate drivers. Exposure (as a component of vulnerability) assessed as low (L), moderate (M) or high (H)*

Driver		**Functional Group**					
		Freshwater and estuarine	**Coastal and inshore**	**Reef***	**Shelf**	**Bathyal**	**Pelagic**
Physiological (direct)	Temperature	H	H	H	M	M	M
	Ocean acidification	L	L	L	L	L	L
	Freshwater input	H	M	M	M	L	L
Large-scale (indirect)	Ocean circulation	L	M	M	H	M	H
	Temperature	H	H	H	M	L	L
	Sea level rise	H	H	L	L	L	L
	Severe weather	H	H	H	L	L	L
	Freshwater input	H	H	M	M	L	L
	Light	H	M	M	L	L	L
	Ocean acidification	–	–	H	–	–	–

Drivers: Temperature (water and air temperature); Ocean acidification (pH decrease); Freshwater input (rainfall, freshwater input, floods and drought); Sea level rise (sea level rise and coastal inundation); Severe weather (cyclonic disturbance and severe weather events); Light (UV).

* Increased ocean acidification is a large-scale driver with particular implications for reefs and has been assessed for this functional group only.

13.2.5.3 Vulnerability of species and functional groups to climate change

The vulnerability assessment framework produced vulnerability rankings (low, moderate or high) for each species in each functional group, for each of the climate change drivers. The assessment produced more than 50 tables of results that are available for request via the editor (J Johnson). These tables include:

- Results tables showing the calculation of vulnerability rankings for each species in each functional group to each of the climate change drivers (55 tables in total)
- Summary tables showing the exposure of each functional group, the sensitivity and inadaptability ranking of each species in each functional group, and the resulting vulnerability to each climate change driver (one table for each functional group – six tables in total)

The vulnerability results for each functional group are summarised in Table 13.3. The main patterns and trends emerging from these results are presented below.

The vulnerability of each functional group to a specific climate change driver depends on the vulnerability rankings of each species within the group. For example, if the majority of species within a functional group have low vulnerability to sea level rise, the overall vulnerability of the functional

group to sea level rise is described as low. Similarly, the overall vulnerability of a functional group to climate change (the sum of all the climate change drivers) depends on the vulnerability of the group to each of the climate change drivers. For example, if a functional group has low vulnerability to seven climate change drivers, it is described as having a low overall vulnerability to climate change (Table 13.3).

These results only consider vulnerability to climate change drivers. The interaction between human activities and climate change drivers, and the potential synergies arising from these interactions are considered in section 13.3.2.

Freshwater and estuarine functional group (4 species): moderate *vulnerability to climate change*

- Species in this group had high exposure to all climate change drivers except for ocean acidification and ocean circulation (Table 13.2). The climate change drivers identified may lead to habitat loss, and cause changes in freshwater input that affect biological productivity and food webs.
- The freshwater whipray *Himantura* cf. *chaophraya* is the most vulnerable species in this group. It is a relatively rare species, and has high habitat and trophic specificity. As species in this group are exposed to the highest number of climate change drivers, the freshwater whipray is potentially the most vulnerable chondrichthyan on the GBR to climate change.
- Three of the four species in this group have high sensitivity (are rare and live in specific habitats). However, these species are adapted to relatively harsh conditions and thus have moderate to low inadaptability (ie they are able to adapt to changing conditions). This compensates for their high exposure and sensitivity.
- This results in an assessment of low or moderate vulnerability for three of the four species in this group, producing a group ranking of moderate vulnerability to climate change (Table 13.3).

Other considerations:

- Adaptive capacity is founded on the principle that these species are able to move to and successfully exploit new areas should conditions in their existing habitats deteriorate. This assumption is untested and should be treated with caution.

Coastal and inshore functional group (47 species): low *vulnerability to climate change*

- Species in this group had high to moderate exposure to climate change drivers (Table 13.2). The most significant drivers were temperature, sea level rise, severe weather events, and changes in freshwater input that can affect biological productivity and food webs.
- The porcupine ray *Urogymnus asperrimus* has high vulnerability to climate change due to its rarity and immobility, and the high to moderate exposure of this group to climate change drivers.
- The sawfishes of the family Pristidae, stingrays (Dasyatidae), eagle rays (Myliobatidae), stingarees (Urolophidae), butterfly rays (Gymnuridae) and cownose rays (Rhinopteridae) had low to moderate vulnerability to climate change. Attributes contributing to the assessment of species as moderately vulnerable included rarity, habitat and trophic specificity and immobility.

- The whaler sharks (Carcharhinidae), weasel sharks (Hemigaleidae) and hammerhead sharks (Sphyrnidae) had low sensitivity and inadaptability (ie high adaptive capacity) resulting in a ranking of low vulnerability to climate change.
- Overall, approximately 70 percent of species in the coastal and inshore group had low vulnerability and over 27 percent had moderate vulnerability to the nine climate change drivers assessed for this group (Table 13.3).
- The group was assessed as having an overall low vulnerability to climate change (Table 13.3).

Reef functional group (19 species): low to moderate *vulnerability to climate change*

- The reef functional group had high to moderate exposure to most climate change drivers (Table 13.2). Temperature, severe weather and ocean acidification were the most significant climate change drivers due to their potential impacts on habitat.
- Species in this group have low to moderate vulnerability to climate change. None of these species were identified as having high vulnerability.
- Species assessed as being moderately vulnerable to climate change included some stingrays (Dasyatidae), longtail carpet sharks (Hemiscylliidae), the tawny nurse shark, *Nebrius ferrugineus*; zebra shark, *Stegostoma fasciatum*; and grey nurse shark, *Carcharias taurus*. These species tended to have moderate habitat specificity and/or immobility.
- Close to 70 percent of these species have a moderate or high dependency on coral reef habitats.
- Species in this group are also generally flexible and can tolerate a range of environmental conditions, have low to moderate trophic specificity and most species are relatively abundant.
- Overall, vulnerability for this group is low to moderate as they generally have high adaptive capacity that counteracts their reliance on specific habitat (Table 13.3).

Other considerations:

- Habitat specificity requires highlighting for sharks and rays inhabiting coral reefs. These species tend to have moderate to high habitat specificity and high exposure, but are relatively flexible and thus have low inadaptability (high adaptive capacity). As in the freshwater and estuarine group, it is assumed that reef sharks and rays will be able to move to and successfully exploit new habitats and resources. Coral reefs have narrow environmental tolerances and this habitat type is considered especially at risk to climate change. The assumption that reef sharks and rays will be able to move to unaffected reefs or locate other habitats that provide the same ecosystem services as coral reefs is untested and should be treated with caution.

Shelf functional group (26 species): low *vulnerability to climate change*

- Species in this group had low to moderate exposure to climate change drivers (Table 13.2). Temperature, ocean circulation and freshwater input were the most significant climate change drivers due to their potential impacts on biological productivity and food webs.
- Twenty-six percent of the species in this group had moderate vulnerability. These species are from a wide range of families but all shared moderate to high rarity and/or limited latitudinal ranges (a proxy for temperature intolerance).

- Most of the other species in the shelf functional group are relatively abundant and widespread, and are relatively flexible, feeding on a wide variety of prey and occurring in a variety of habitats and locations. Consequently they were assessed as having low vulnerability to climate change.
- Some species are only moderately mobile which may reduce their ability to adapt to changing conditions.
- Low to moderate exposure, low sensitivity and low inadaptability for most species gave this group an overall ranking of low vulnerability to climate change (Table 13.3).

Other considerations:

- Little is known about the habitats, biodiversity and ecological processes occurring in the shelf habitats. This introduces more uncertainty in the assessment of this group and highlights the need for more research in these habitats.

Bathyal functional group (54 species): low *vulnerability to climate change*

- Species in this group had low exposure to climate change drivers with the exception of ocean circulation (moderate) and temperature (moderate) (Table 13.2).
- These species have low habitat specificity but many are relatively rare (high sensitivity).
- Bathyal species exploit a variety of prey and can potentially tolerate a range of environmental conditions, but are moderately immobile.
- Low exposure combined with low to moderate inadaptability results in a group assessment of low vulnerability to climate change (Table 13.3).

Other considerations:

- The habitats, biodiversity and ecological processes occurring on the continental slope and beyond are poorly known. For example, some species may potentially be present in larger numbers but surveys of bathyal habitats are lacking. While changing rarity from 'high' to 'low' would not affect the outcome of this vulnerability assessment, it highlights the need for more research in these habitats.

Pelagic functional group (10 species): low *vulnerability to climate change*

- Species in this group had low exposure to climate change drivers except for ocean circulation (high) and the direct effects of temperature change (moderate) (Table 13.2).
- The devil rays (*Manta birostris, Mobula thurstoni* and *M. eregoodootenkee*) and whale shark *R. typus* are the most vulnerable species in this group as they are plankton feeding specialists, and the whale shark and bentfin devil ray, *M. thurstoni*, are relatively rare. However, these species have low exposure to most climate change drivers so are ranked as having low overall vulnerability to climate change.
- All species in this group have low habitat specificity and low inadaptability (they are flexible species) with the exception of plankton feeding specialists.
- The low exposure and inadaptability give this group vulnerability rating of low (Table 13.3).

Table 13.3 *Vulnerability to the physiological and large-scale climate-change drivers by percentage of species within each functional group. Vulnerability assessed as low (L), moderate (M) or high (H). Numbers in parentheses are numbers of species*

Driver		Functional Group					
		Freshwater and Estuarine (4 species)	Coastal and Inshore (47 species)	Shelf (26 species)	Reef (19 species)	Bathyal (54 species)	Pelagic (10 species)
Physiological	**Temperature**	25.0% H (1) 50.0% M (2) 25.0% L (1)	2.1% H (1) 27.7% M (13) 70.2% L (33)	0.0% H (0) 23.1% M (6) 76.9% L (20)	0.0% H (0) 47.4% M (9) 52.6% L (10)	0.00% H (0) 63.0% M (34) 37.0% L (20)	0.0% H (0) 40.0% M (4) 60.0% L (6)
	Ocean acidification	100% L (4)	100% L (47)	100% L (26)	100% L (19)	100% L (54)	100% L (10)
	Freshwater input	25.0% H (1) 50.0% M (2) 25.0% L (1)	0.00% H (0) 29.8% M (14) 70.2% L (33)	0.0% H (0) 23.1% M (6) 76.9% L (20)	0.0% H (0) 47.4% M (9) 52.6% L (10)	100% L (54)	100% L (10)
Large-scale	**Ocean circulation**	100% L (4)	0.00% H (0) 29.8% M (14) 70.2% L (33)	3.9% H (1) 19.2% M (5) 76.9% L (20)	0.0% H (0) 47.4% M (9) 52.6% L (10)	0.00% H (0) 63.0% M (34) 37.0% L (20)	20.0% H (2) 20.0% M (2) 60.0% L (6)
	Temperature	25.0% H (1) 50.0% M (2) 25.0% L (1)	2.1% H (1) 27.7% M (13) 70.2% L (33)	0.0% H (0) 23.1% M (6) 76.9% L (20)	0.0% H (0) 47.4% M (9) 52.6% L (10)	100% L (54)	100% L (10)
	Sea level rise	25.0% H (1) 50.0% M (2) 25.0% L (1)	2.1% H (1) 27.7% M (13) 70.2% L (33)	100% L (26)	100% L (19)	100% L (54)	100% L (10)
	Severe weather	25.0% H (1) 50.0% M (2) 25.0% L (1)	2.1% H (1) 27.7% M (13) 70.2% L (33)	100% L (26)	0.0% H (0) 47.4% M (9) 52.6% L (10)	100% L (54)	100% L (10)
	Freshwater input	25.0% H (1) 50.0% M (2) 25.0% L (1)	2.1% H (1) 27.7% M (13) 70.2% L (33)	0.0% H (0) 23.1% M (6) 76.9% L (20)	0.0% H (0) 47.4% M (9) 52.6% L (10)	100% L (54)	100% L (10)
	Light	25.0% H (1) 50.0% M (2) 25.0% L (1)	0.00% H (0) 29.8% M (14) 70.2% L (33)	100% L (26)	0.0% H (0) 47.4% M (9) 52.6% L (10)	100% L (54)	100% L (10)
	Ocean acidification	NA	NA	NA	0.0% H (0) 47.4% M (9) 52.6% L (10)	NA	NA
Overall group vulnerability		**Moderate**	**Low**	**Low**	**Low to moderate**	**Low**	**Low**

Red text highlights the vulnerability ranking that accounts for the majority of the species in the functional group. Blue text highlights where two vulnerability rankings are evenly represented amongst the majority of species in that functional group. NA = not applicable . Number in brackets represents number of species within each functional group within that category

Other considerations:

- The oceanographic and ecological processes driving the pelagic environments of the outer reef and Coral Sea are not well understood. This introduces more uncertainty in the assessment of this group and highlights the need for more research in these habitats.
- Many of these species are highly migratory and travel between oceans. These species may rely on a biological 'calendar of events' that affects their migration and movement patterns. The biological events that these species rely on may be significantly affected by global climate change, but have not been considered in this assessment.

13.3 Linkages

13.3.1 Linkages between sharks and rays and marine ecosystems

Sharks and rays occupy ecological niches at the upper levels of marine food webs, and are thus closely linked to many other parts of the marine ecosystem. Changes occurring in habitats, or in biological processes operating at lower levels of the food web, can cause a chain of events that ultimately affect sharks and rays.

The effects of climate change on these habitats and processes are considered in other chapters of this volume, specifically chapters on species groups (marine microbes, plankton, mangroves, seagrass, coral reefs, invertebrates and fishes), and on habitats and processes (reefs, pelagic and coastal and estuarine, physical oceanography and coral reef resilience). The main linkages between these habitats and processes and sharks and rays are outlined below.

Many sharks and rays may have specific habitat requirements and use certain habitats as foraging grounds, breeding grounds or to provide shelter from predators. Seagrass beds, mangroves and other estuarine habitats are important breeding and nursery grounds for a number of sharks[8,26,65]. Many species such as tiger sharks and whaler sharks also use these habitats as foraging grounds (eg (Blaber et al.[3], Heithaus et al.[26]). Habitats may be particularly important at certain stages in the life cycle of sharks and rays. For example, juvenile sharks have been found to use nursery grounds to avoid predators, which increases survival rates of young sharks[27,67]. There is also increasing evidence of philopatry in some sharks and rays. These species repeatedly return to the same habitats in specific locations at different times in their life cycle to mate, give birth or feed[31]. This increases their dependency on particular habitats in specific locations.

Habitats also provide food and shelter for many prey species and the degradation or loss of these habitats may decrease the availability of suitable prey. Seagrasses and mangroves are important habitats for other marine species such as fishes, crustaceans, marine turtles and marine mammals[6,9,49]. In some cases, coastal habitats are linked to coral reefs offshore. For example, the diversity and abundance of reef fish may be linked to the presence of coastal mangroves[47]. Some reef fishes rely on particular types of coral for food or shelter. Corals also create a complex structure similar to trees in a forest, creating habitat for a great diversity of marine species that sharks and rays prey upon. The loss of coral reef habitat may result in declines in half the reef's species of teleost fishes (Munday et al. chapter 12).

Changes to ecological processes may also have indirect impacts on sharks and rays by altering prey availability. In coastal and estuarine ecosystems, biological productivity (the process where physical elements are cycled into biomass) and nutrient cycling are closely linked to photosynthesis by marine plants and the activity of microbial communities. These processes create edible food (plants and micro-organisms) that forms the foundation of many marine food webs that drive the availability of prey. Physical processes such as freshwater runoff, currents and upwelling also affect biological productivity[11]. For example, the abundance of prawns and fishes such as barramundi are correlated with rainfall and river flow[46,70]. In pelagic and bathyal ecosystems, biological productivity is linked to upwelling currents that bring nutrients into these ecosystems. These nutrients feed plankton that in turn, are consumed by many marine organisms that sharks and rays ultimately prey upon.

13.3.2 Constraints to adaptation

Chondrichthyan fishes have existed in various forms for some 400 million years and have evolved life history traits that have allowed them to be highly successful over evolutionary time. However, these same traits (long lived animals with relatively low mortality rates and reproductive outputs) mean that sharks and rays evolve very slowly[41], and are unlikely to be able to adapt to changing conditions over the next 100 years through evolutionary processes. Furthermore, climate change is occurring at unprecedented rates making it more unlikely that sharks will be able to adapt through evolution. It is more likely that sharks will adapt to climate change by changing their behaviour, distribution and exploiting new opportunities. This will alter the patterns of abundance and distribution observed today[83]. In the GBR, species that are able to tolerate and exploit warming conditions will likely expand their ranges south, a pattern that has already been observed in marine ecosystems elsewhere (see section 13.1.6). However, sharks and rays that are unable to tolerate warming conditions, or are unable to compete with the influx of northern species, will retreat southwards and may be lost from the GBR.

It should be noted that while chondrichthyans have survived mass extinction events over evolutionary time, the number of species of sharks and rays present today is significantly less than the shark and ray diversity evident in fossil records[24]. Consequently, the extinction of even a few species of modern sharks or rays represents a significant loss to global chondrichthyan diversity.

Many sharks and rays are assessed as having low vulnerability to climate change because they have low inadaptability. These sharks are able to compensate for the impacts of climate change through physiological responses, by moving away from adverse conditions, feeding on alternative prey or finding and successfully establishing themselves in alternative habitats. The capacity for physiological adaptation is determined by the biological traits of each species, but the capacity for sharks to move and exploit alternative prey or habitats depends on these alternative habitats and prey being available. This is especially relevant for reef species as coral reefs require a narrow band of environmental conditions and thus, only thrive in specific locations.

13.3.3 Synergies between climate change and other pressures

Existing pressures

The pressure from human activities such as fishing may increase vulnerability of a range of marine species to climate change[52]. Around the world sharks and rays are under increasing pressure from fishing and habitat loss and significant declines in many shark populations have been recorded[5,76,83]. Their conservative life history traits (see section 13.1.1) mean that human pressures can cause, and have caused the removal of large numbers of sharks in relatively short time periods, resulting in the collapse of these populations. Once depleted, it may take decades for shark populations to recover[64]. The reduction of shark populations, and subsequent reduction in reproductive output, may reduce the capacity of shark populations to absorb or recover from climate change impacts

In the GBR, human pressures on sharks and rays are increasing[10] and some sharks and rays in the GBR are threatened with extinction. The catch of sharks and rays in commercial fisheries, mostly coastal and inshore species, has increased four-fold since 1993[53]. Fishing pressure may have also driven population declines in reef species such as grey reef and white tip reef sharks, which have experienced declines of over 80 per cent on some reefs[57].

Coastal habitats on the GBR such as seagrass meadows, inshore reefs and mangroves are also under increasing pressure. Coastal development such as expansion of urban centres, aquaculture, agriculture and the infrastructure associated with these developments (roads, ports, causeways etc), have led to significant changes in coastal areas. Impacts may be caused by land clearing or reclamation, modifying catchments through dams and weirs, changing water flows and coastal hydrology, and the input of pollutants such as pesticides and nutrients that can poison organisms or cause algal blooms that disrupt marine ecosystems[25,32]. While large-scale destruction of wetlands, mangroves, seagrasses and other habitats has not occurred in recent times, localised losses have been recorded. Furthermore, the extent to which these habitats have been altered since European settlement in the 1800s is unknown[20]. Degradation of these habitats may result in loss of critical nursery or foraging grounds for sharks and rays, and affect the availability of prey. These sorts of impacts add to the effects of climate change.

The immediate concern is the current mortality and sustainability of these populations, and the protection of their habitats. The potential impacts of climate change should be considered in management strategies addressing these pressures.

Future pressures

The likely human responses to climate change are difficult to predict and are examined in chapter 23 (Fenton et al. chapter 23). The following scenarios are speculative and are based on observations of human modifications to the environment currently evident in the GBR and around the world.

Human responses to climate change may increase existing pressures. Rising sea levels may result in the construction of levees and barriers to prevent flooding. These structures could further disrupt freshwater flows, hydrology and connectivity of coastal habitats such as salt marshes, mangroves and seagrasses[34]. Additionally, these structures could reduce the ability of these habitats to adapt to rising sea levels by colonising suitable areas inland, leading to the loss of these habitats in some areas.

Greater variability in rainfall could prompt the construction of more dams and weirs to store water, and increase pressure on water supplies during droughts. Reduced freshwater flow would reduce the number and size of freshwater pools that provide refuge for aquatic species during droughts, and increase salinity in upper estuarine habitats. Potential increases in catchment modification and water use for human consumption are likely to have significant impacts on estuarine and coastal habitats, ecological processes and biological connectivity which will have flow-on effects for sharks and rays, especially freshwater and estuarine species.

The expansion of deepwater fisheries could have significant impacts on bathyal sharks. Many deepwater sharks and rays are even more vulnerable to fishing pressure, as they are less abundant than other sharks, have even slower growth and reproductive rates[19,84,85], and occur in habitats with relatively low biological productivity. Worldwide, several stocks of deepwater chondrichthyans have already been overfished[21]. Although there is minimal deepwater fishing in the GBR region, the development of such fisheries could have serious consequences for these species and reduce their ability to cope with climate change.

13.3.4 Integrating synergies with climate change vulnerability

Freshwater and estuarine, and coastal and inshore sharks and rays

Coastal habitats (rivers, estuaries, seagrasses and mangroves) are already under significant pressure from human activities. Some inshore coral reefs are showing signs of decline and wetlands and mangroves have experienced localised losses. Future human responses to rising sea levels and greater variability in rainfall may result in increased pressure on freshwater and coastal habitats through the construction of dams or levee banks and impoundment of water. These pressures may increase rates of habitat loss and degradation and disrupt the ecological processes that regulate prey availability.

Freshwater sharks and rays are generally at risk around the world due to their restricted distribution, their proximity to human pressures and the extent of human disturbance to these habitats[38]. Three of the four species in this functional group are listed by the IUCN as threatened with extinction, highlighting the conservation concern for this group. As these species are already facing extinction, additional pressures from climate change could create situations where these species cannot absorb or recover from cumulative impacts, resulting in extinction.

Human impacts on coastal and inshore sharks and rays in the GBR have significantly increased[10]. Given their conservative life history traits, the poor track record of shark fisheries around the world, and the lack of data regarding the sustainability of GBR shark fisheries, these pressures are likely to increase the vulnerability of coastal and inshore sharks to climate change.

There is sufficient evidence to suggest that these additional pressures and synergies will increase the vulnerability of these sharks and rays to climate change. Consequently, the authors conclude that *freshwater and estuarine* species should be considered as **highly vulnerable** to climate change, and the *coastal and inshore group* be considered **moderately vulnerable** to climate change.

Bathyal and shelf sharks and rays

There is little information about the biology, abundance, distribution, and ecological processes that influence sharks and rays found in shelf and bathyal habitats of the GBR. This lack of information is of concern, as this assessment will not have fully considered the exposure to potential climate change impacts. Deepwater species are generally considered to have low growth rates and reproductive outputs, and inhabit environments with low biological productivity. These traits may make bathyal species more vulnerable to climate change, particularly if deepwater currents and upwellings change.

Pelagic sharks and rays

Pelagic sharks and rays are highly migratory species that may encounter significant pressures from both climate change and human activities throughout their range. Many of these pressures are poorly documented and could exert a significant cumulative impact on these species. For example, highly migratory species may encounter multiple fisheries during long distance movements. Highly migratory species may also follow seasonal migration patterns dependant on biological events such as plankton blooms[80]. As climate change is a global phenomenon, climate change impacts may occur throughout the range of these species resulting in a significant cumulative impact. The processes that regulate the movement patterns of many migratory sharks and rays are not well understood, and the impacts of high seas fisheries are poorly documented. Nevertheless, the authors consider that cumulative impacts across the range of these species may be significant, and caution that these pressures may significantly increase the vulnerability of these species to climate change.

13.4 Summary and recommendations

13.4.1 Major vulnerabilities to climate change

This assessment has highlighted a number of factors that drive the vulnerability of GBR sharks and rays to climate change.

- The potential synergistic impacts of fisheries on sharks and rays in the GBR
- Degradation and loss of coastal habitats such as estuaries, seagrasses and mangroves through climate change impacts and human pressures
- Disruption of ecological processes that drive biological productivity and prey availability by rainfall and oceanographic changes.

Additionally, threatened species and particular species groups (see section 13.2.5.3) may be especially vulnerable to climate change given existing pressures, reduced populations and/or biological attributes.

13.4.2 Potential management responses

Under the *Great Barrier Reef Marine Park Zoning Plan 2003*, 33 percent of the Great Barrier Reef Marine Park is zoned as Marine National Park Zones that do not allow extractive activities such as fishing and collecting. These zones protect both habitats and the sharks and rays present within these zones. The joint State and Commonwealth *Reef Water Quality Protection Plan* and Fisheries Habitat Areas declared by the Queensland Government also help to protect coastal and estuarine habitats.

The Queensland Department of Primary Industries and Fisheries (QDPIF) has legislative responsibility for management of Queensland's fisheries. The take of grey nurse sharks, great white sharks and freshwater sawfish is prohibited and shark finning is restricted, but there are few other fisheries regulations that relate specifically to the take of sharks and rays. Structural adjustment of the net fishery in 2004 resulted in the buyout of 59 net licences, reducing both catch and effort. Nevertheless, there are concerns about rising effort in the commercial net fishery and the take of sharks and rays. In 2002, the QDPIF issued an investment warning for the fishery stating that increases in level of catches or fishing effort might not be recognised in future management arrangements. More recently, risk assessments have identified a number of species in the GBR at high risk to fishing[22,62]. Assessments carried out under the *Environment Biodiversity and Conservation Act 1999* have also raised concerns about the long-term ecological sustainability of the fishery. Management arrangements for the Queensland East Coast Inshore Finfish Fishery are currently being reviewed.

In terms of climate change, a number of management actions may potentially reduce the impacts of climate change on sharks and rays in the GBR. These are related to the major vulnerabilities identified.

1) Addressing human activities that contribute to climate change, namely the production of greenhouse gases.
2) Improving fisheries management arrangements for fisheries in the GBR that harvest sharks. Specifically, improving information on the effort, catch (both target and bycatch) and stock assessments for these fisheries to ensure long-term sustainability, especially in the context of impacts from other factors such as climate change.
3) Continuing to protect and preserve critical habitats, particularly freshwater, estuarine, inshore, and reef habitats. This includes preserving the ability of these ecosystems to cope with pressures, including climate change, by protecting these habitats and maintaining the ecological processes that allow them to function.
4) Protect and conserve threatened species, and the species identified in this assessment as being highly vulnerable to climate change.
5) Include vulnerability to climate change in the development of ecological risk assessments for fisheries, assessments of conservation status and the development of conservation and management strategies.
6) Educate communities about the trends, threats and potential impacts of climate change on sharks and rays, and provide them with meaningful ideas on how they could take action to address these impacts.

13.4.3 Further research

Relatively little research has been carried out on sharks and rays in the GBR and there is a clear need for more information[16]. Future research could refine and clarify some impacts and vulnerabilities discussed in this chapter. These areas include research to improve the management, conservation and sustainability of sharks and rays to human pressures and research focused specifically on the impacts of climate change on sharks and rays. Key research areas are outlined below.

1) Research to improve the sustainability of fisheries and their impacts on sharks and rays in the GBR. Reducing risks posed by the major human impacts on sharks and rays in the GBR will decrease their vulnerability to climate change. Potential research areas include:
    a) improved information on fishing effort and the composition and amount of catch and bycatch
    b) improved information on the life history, movement and habitat use of key species taken by fisheries in the GBR
    c) development of robust risk assessments, stock assessments and sustainability targets for GBR fisheries that take sharks and rays
    d) ongoing fisheries monitoring to monitor trends in catch and sustainability
2) Research to clarify links between climate change and GBR sharks and rays. This would identify specific dependencies and critical processes that help to inform and prioritise management actions. Potential research areas include:
    a) physiological affects of climate change drivers (eg temperature, pH) on GBR sharks and rays (eg effects on growth, metabolism, reproduction), and the long term consequences of these effects
    b) ecology of key species including movement and habitat use, diet and behaviour, and linkages between these attributes and habitats and processes
    c) mechanisms through which human activities influence these habitats and processes
    d) ecosystem models to refine the predicted impacts of climate change and the cumulative impacts and synergies of climate change and human impacts
3) Research to support the conservation of threatened species and species that are highly vulnerable to climate change including:
    a) life history, movement and habitat use of these species
    b) identification of key threatening processes
    c) monitoring the effectiveness of conservation measures
4) Research to improve knowledge and understanding of the chondrichthyan fauna of the GBR, including:
    a) a comprehensive survey of the chondrichthyan fauna of the GBR to document species and their distribution
    b) taxonomic work to identify and adequately catalogue the diversity of the GBR chondrichthyans

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