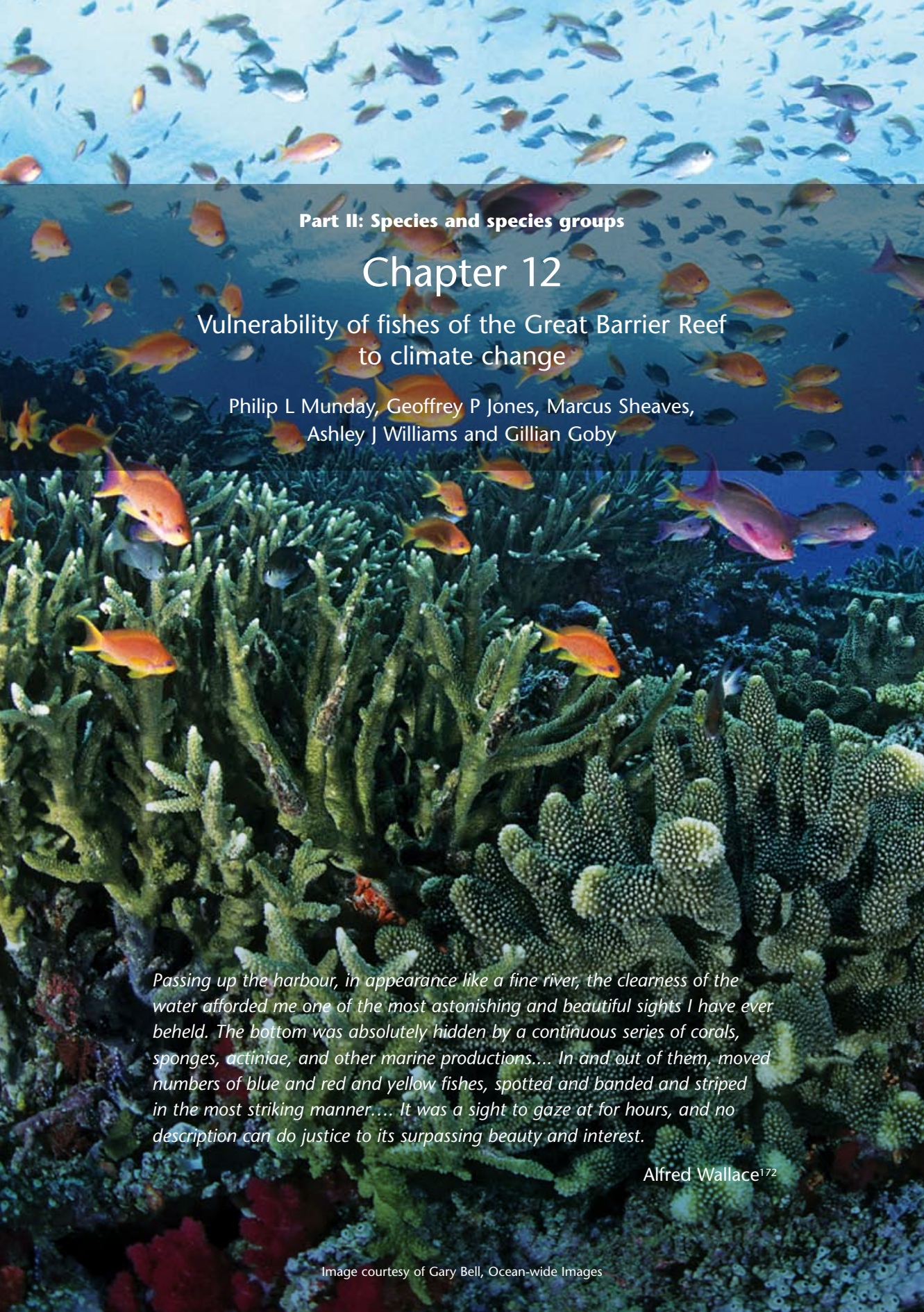

Part II: Species and species groups

Chapter 12

Vulnerability of fishes of the Great Barrier Reef to climate change

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Passing up the harbour, in appearance like a fine river, the clearness of the water afforded me one of the most astonishing and beautiful sights I have ever beheld. The bottom was absolutely hidden by a continuous series of corals, sponges, actiniae, and other marine productions.... In and out of them, moved numbers of blue and red and yellow fishes, spotted and banded and striped in the most striking manner.... It was a sight to gaze at for hours, and no description can do justice to its surpassing beauty and interest.

Alfred Wallace[172]

Image courtesy of Gary Bell, Ocean-wide Images

12.1 Introduction

Climate change has already caused significant impacts to Earth's ecosystems. Shifts in plant and animal biogeographic ranges[125], changes to population abundance[74,173], adjustments in the timing of seasonal activities[74,144,171] and the establishment of invasive species[173] have all been attributed to climate change. Most examples of biological impacts from climate change involve terrestrial species, however, similar effects have been observed in marine species, especially from temperate regions[5, 165,55,162,63]. The impact of climate change on coral reefs has also been widely considered, mostly with regard to coral bleaching and the degradation of coral communities[68,75]. Much less attention has been given to the impact that climate change will have on other organisms that are associated with coral reefs. Fish are one of the most conspicuous and diverse components of tropical marine ecosystems, yet how they will be affected by climate change has not been comprehensively assessed[142,114].

12.1.1 Fishes of the Great Barrier Reef

Over 1500 species of fish are estimated to occur on the Great Barrier Reef (GBR)[118], ranging from tiny gobies weighing less than a gram and living just a few months[43], to giant groupers weighing many hundreds of kilograms and living decades[137,126]. Most fish species found on the GBR are widespread in the tropical western Pacific, and many have distributions that extend into the Indian Ocean and central Pacific[137]. This means that the fish fauna of the GBR has strong affinities with neighbouring regions, such as tropical Western Australia, south-east Asia and the islands of the western and central Pacific.

The GBR is a complex network of different habitats for fishes, including shallow coastal and estuarine waters, coral reefs, a variety of inter-reef environments, and the continental slope with accompanying deepwater pelagic zone. Each of these broad habitat types contains a characteristic suite of species. The vast majority of GBR fish species occur on coral reefs. A smaller number of species occupy coastal waters and inter-reef areas, while others are more mobile and inhabit the pelagic zone around reefs. Characteristic fishes of coral reefs include the butterflyfishes (family: Chaetodontidae), angelfishes (Pomacanthidae), wrasses (Labridae), parrotfishes (Scaridae), damselfishes (Pomacentridae) and surgeonfishes (Acanthuridae)[32]. In terms of species diversity, coral reef fish assemblages are dominated by wrasses (Labridae), damselfishes (Pomacentridae), gobies (Gobiidae) cardinalfishes (Apogonidae), groupers (Serranidae) and blennies (Blennidae). Although some coral reef fishes can reach large sizes (greater than 1 metre), the vast majority of species are relatively small and many are less than 100 mm in length[115].

A diverse range of taxa, including emperors (Lethrinidae), snappers (Lutjanidae), coral breams (Nemipteridae), goatfishes (Mullidae), grunters (Teraponidae), and puffers (Tetraodontidae) occur on the soft sediment and hard-bottom areas between reefs[174,29]. Trevallies (Carangidae), tunas and mackerels (Scombridae) are common in the pelagic zone around reefs.

There is considerable structure in the spatial distribution of fishes within the GBR. Most strikingly, the relative abundance of many species changes dramatically between inshore, mid-shelf and outer-shelf reefs[181,146,179]. Some species are most abundant on inshore reefs, whereas other species are more abundant on mid- or outer-shelf reefs. Differences in habitat type, food supply and physical conditions across the shelf are likely to be responsible for this distinct cross-shelf pattern of community structure. The distribution of species also changes along the length of the GBR, although the pattern is not

as distinct as that observed across the shelf[179]. Finally, the distribution of fishes varies within reefs. Many reef fishes occur in a relatively narrow depth range or are consistently found in a particular reef zone (eg forereef, reef flat, backreef or lagoon)[147,120]. Consequently, despite unpredictable spatial and temporal variation in the abundance of individual species, there are relatively predictable patterns of community structure within reefs, across the continental shelf, and along the length of the GBR.

Fish have a significant presence in all major feeding groups on the GBR – they are herbivores, carnivores, planktivores, omnivores and piscivores. They are the dominant large predators on reefs and are important for energy transfer throughout the reef ecosystem. Some species also have key functional roles[9]. For example, grazing herbivorous fishes consume macroalgae that might otherwise overgrow and smother corals[103,104]. Other species facilitate the settlement of corals and coralline algae by removing sediment and fine algae from the substratum[166,9]. Reef fishes also have high economic value. The diversity and abundance of fishes on the GBR underpins a multi-billion dollar regional tourism industry (A$6.1 billion) and some species support important commercial and recreational fisheries, worth an estimated A$145 million and A$610 million (GDP) respectively per annum[57,1]. Clearly, substantial changes to the distribution or abundance of fishes on the GBR due to climate change could have serious consequences for the ecological function of the GBR and the economies and social well-being of people that depend on it.

12.1.2 Critical factors for fish survival

Nearly all GBR fishes have a life cycle that includes a pelagic larval stage, which lasts for a period of weeks to months, depending on the species[97]. For species where adults are also pelagic, larvae can recruit directly into the juvenile population. For most other species, however, the pelagic larvae must transition to a benthic existence to join the juvenile and adult population. When they are sufficiently well developed, larvae metamorphose and settle to the reef[98], often in the same habitat used by juveniles or adults[21]. After settlement, most coral reef fishes are relatively sedentary, although some species move from juvenile to adult habitats as they develop[99]. A few species, such as some snappers and groupers, settle into coastal and estuarine locations and migrate to reefs or deeper inter-reef areas as juveniles or subadults[156].

Climate change will affect populations and communities of fishes on the GBR through a range of impacts on either the larval, juvenile or adult phases. Dispersal and survival patterns of fish larvae play a key role in the dynamics of adult populations[47,45,46] and the ecological and genetic connectivity between populations[152,38]. The larval stage of reef fishes is highly sensitive to environmental conditions[98] and any changes to the growth, survival, or range of larval dispersal patterns brought about by climate change could have significant consequences for the distribution and abundance of adult populations.

The impact of climate change on the structure of coral reef habitats will also have far-reaching consequences for fish populations and communities. Recent episodes of coral bleaching from elevated sea temperatures have seriously degraded reefs around the world[176]. The loss of coral from bleaching has caused significant declines in the diversity and abundance of reef fishes in some places[184,135] and this effect will be magnified if the structural complexity of reefs declines as a result of continued degradation[56]. The amount of suitable habitat for reef fishes will be further compromised if the effects

of coral bleaching interact with other disturbances that kill live coral, such as outbreaks of crown of thorns starfish or terrestrial pollution. Although the GBR is currently in relatively good condition, it cannot escape the global affects of climate change. The interacting effects of climate change and other stressors have the potential to substantially alter the structure of fish communities on the GBR.

Here we use available data for temperate and tropical marine fishes to assess and predict the likely impacts of climate change on the life histories, ecology, and distribution of fishes on the GBR. We limit our analysis to teleost fishes (bony fishes); sharks and rays (cartilaginous fishes) are considered in a separate chapter (Chin and Kyne chapter 13). We first examine the exposure and sensitivity of tropical marine fishes to changes in physical and oceanographic conditions predicted to occur due to climate change on the GBR by the end of this century (Lough chapter 2). We then explore the possible impacts that these sensitivities will have on life histories, population dynamics, community structure and geographical distributions of fishes on the GBR. We assess the possible consequences for fisheries and consider how climate change might interact with other human-induced impacts. There is considerable uncertainty about the magnitude and in some cases even the direction, of physical changes that will occur on the GBR because of climate change. These uncertainties mean that our conclusions are tentative and often speculative. Nevertheless, our analysis identifies areas of concern regarding the possible effects of climate change on GBR fishes and critical areas for future management and research.

12.2 Vulnerability of fishes to climate change: exposure and sensitivity

12.2.1 Changes in water temperature

All species have thermal optima where physiological processes are maximised or operate most effectively. This thermal range of peak performance is narrower than the thermal tolerance limits exhibited by the species and may differ throughout the species geographical distribution due to acclimation or local-adaptation to different temperature regimes[64]. Fishes are ectotherms and temperature has a critical effect on their physiology and whole-organism function. Changes of a few degrees Celsius in ambient temperature can influence physiological condition, developmental rate, growth rate, swimming ability, reproductive performance, and behaviour[185]. Even if coral reef fishes are not living near their upper thermal limits[112], the predicted 1 to 3°C rise in mean sea temperature on the GBR by 2100 (Lough chapter 2) will almost certainly influence their functional capacity, life-histories and behaviour. The magnitude of any effects, however, are difficult to predict because: i) most studies on the effects of temperature on organism function have been conducted on temperate fishes; ii) tropical marine fishes may be more sensitive to elevated temperature than temperate marine fishes, because annual variation in water temperature experienced by tropical species is generally less than that experienced by temperate species; iii) cellular and physiological responses to temperature will interact in complex ways with environmental factors, such as food availability, to determine the outcome of higher temperature on individual phenotypic and life history traits; and iv) there is considerable potential for acclimation and adaptation to changes in temperature.

Fishes are particularly sensitive to temperature during their early life history. Across a range of species, embryonic development rate increases nearly threefold for every 10°C increase in temperature[143]. Therefore, an increase in water temperature of 1 to 3°C on the GBR could shorten the incubation period of eggs for both pelagic and demersal spawning fishes. After hatching, increased temperature tends to increase larval growth rate, decrease the age at metamorphosis, and increase swimming ability[11,76]. In a recent experimental analysis, Green and Fisher[58] showed that larval duration of the anemone fish *Amphiprion melanopus* was 25 percent shorter, growth rate was higher, and swimming ability enhanced at 28°C compared to 25°C. These traits could all potentially improve the survival prospects of larval fish by reducing the time they spend in the pelagic environment and improving their ability to feed and escape predators.

There is increasing evidence that the survival of larval coral reef fishes is linked to growth rate, with individuals from strong recruitment pulses often exhibiting higher growth rates during the larval period than those from weak recruitment pulses[155,12,183]. Several studies have found a positive correlation between larval growth rate and ocean temperature[105,183] and one[110] found that temperature had a much greater influence on larval growth than did food supply. Together, these results suggest that the 1 to 3°C increase in sea temperature predicted for the GBR might not, by itself, be detrimental to the survival of larval fishes.

In general, the growth rate of fishes increases with temperature, up to an optimal temperature, after which it declines rapidly with increasing temperature[82]. However, this deceptively simple relationship is affected by food availability. A positive relationship between growth rate and temperature only occurs if fish are able to increase their food intake at higher temperatures. Growth rate declines with increasing temperature for fishes on a fixed and restricted food ration because the energetic cost of basic metabolic maintenance increases with temperature[82]. This means that any growth advantage from increased temperature could be suppressed if food availability is limited. Of course, growth rate will decline sharply if increasing temperature causes a serious reduction in food availability. For example, slower growth appears to have occurred in three species of herbivorous damselfishes during warm El Niño conditions in the Galápagos Islands[108]. The green and red algae preferred by these damselfishes was largely replaced by brown algae of lower nutritional value during the warm period[108], probably causing a food shortage that curtailed growth rates and left tell-tale check marks in otoliths. The impact of increased ocean temperature on the growth rate of fishes on the GBR is difficult to predict without knowledge of how food availability and feeding behaviour will be affected, and this is likely to be species specific.

Reproduction of fishes on the GBR tends to be highly seasonal, often peaking in spring or early summer, although the precise pattern differs greatly among species[140]. Increasing sea temperature appears to trigger the start of the breeding season in at least some tropical reef fishes[36,40,151,67], including coral trout, *Plectropomus leopardus*, on the GBR[153]. Increased temperatures could cause an earlier start to the breeding season in these species, and possibly a longer breeding season if thermal limits for reproduction are not exceeded. Other species use photoperiod, or a combination of photoperiod and temperature, to cue the start of the breeding season. The timing of reproduction in these species might not be as strongly influenced by elevated temperature, however, their reproductive success could be compromised if higher water temperatures caused a mismatch between the timing of the breeding season and the optimal conditions for survival and dispersal of larvae[49].

Reproduction is only possible within a narrow range of the temperatures that can be tolerated by adults[170]. Consequently, elevated temperatures could depress reproductive success in populations that are already living near their optimal thermal environment for reproduction. Ruttenberg et al.[150] found a bell curve relationship between temperature and mass-specific egg production of southern whitetail major, *Stegastes beebei*, in the Galápagos Islands. Egg production declined from a peak near 25°C to lowest rates at 20°C and 27°C. This suggests that an increase in temperature is not always beneficial to reproductive output. The 1 to 3°C increase of sea temperature predicted for the GBR (Lough chapter 2) could potentially have positive or negative effects on the reproductive output of reef fishes, depending on whether or not they are residing in locations close to their thermal tolerance limits for reproduction. Some species from predominantly temperate water fish families (eg pink snapper, *Pagrus auratus*: Sparidae) already appear to be at their thermal limit for reproduction in tropical water[158] and their populations on the GBR may decline as ocean temperature increases.

Sex determination is temperature sensitive in some marine fishes[44]. For example, individuals in low latitude populations of the Atlantic silverside, Menidia menidia, usually develop into females early in the season when temperatures are low and develop into males late in the season when temperatures are higher[37]. There is currently little evidence for temperature dependent sex determination in GBR fishes.

12.2.2 Changes in ocean chemistry

Atmospheric carbon dioxide (CO_2) concentrations have increased 30 percent from an estimated 280 parts per million in pre-industrial times to over 370 parts per million today[78]. Depending on emission scenarios, CO_2 concentrations are predicted to reach 540 to 979 parts per million by the end of the century[78]. The amount of CO_2 dissolved in the ocean increases as atmospheric partial pressure of CO_2 increases. Additional CO_2 reacts with water to form carbonic acid, which through a series of reactions leads to a decline in pH and a shift in the carbonate-bicarbonate ion balance[50].

Oceanic pH is predicted to drop 0.4 to 0.5 points by 2100[145] (Lough chapter 2). This would make the ocean more acidic than at any time in the past 400,000 years[50]. The sensitivity of tropical marine fishes to changes in pH of this magnitude is largely unknown, although the behaviour of some marine fishes (eg snapper) is sensitive to pH changes only slightly beyond the range predicted[91]. In past decades, the acidification of lakes by atmospheric pollutants has caused significant reductions in the growth rate, reproductive activity and survival of freshwater fishes, which has led to serious declines in populations of some lake species[80]. Although the decrease in ocean pH as a result of climate change is not expected to be as severe as that induced by acid pollution in freshwater lakes, the impact of reducing pH using elevated CO_2 levels appears to be more dramatic than an equivalent reduction in pH using acids[79]. Consequently, there is room for concern that elevated levels of dissolved CO_2 and decreased pH might have some effect on marine fishes. Fish eggs are much more sensitive to pH changes than are juveniles and adults[24]. Consequently, the largest effects of acidification are likely to be on reproductive performance, which might flow through to population replenishment if the impacts are sufficiently large.

Increased levels of dissolved CO_2 not only acidify the ocean, they also act to decrease the pH of animal tissue[131]. In fishes, internal pH level is controlled by the exchange of ions, mostly across the gills, and small changes in internal or external pH can be readily compensated[34]. Although this compensatory

mechanism is not detrimental in the short-term, ultimately it might have some physiological costs, especially for species such as pelagic fishes with high metabolic rates[131].

Reduction in the saturation state of carbonate species (especially aragonite) as a result of elevated levels of dissolved CO_2 is expected to have serious consequences for calcification rates of coralline algae, corals, and other calcifying invertebrates[50,88]. This could reduce food supply of some coral, plankton and invertebrate-feeding fishes. A reduced carbonate saturation state could also potentially affect skeletal formation in larval fishes. Skeletal growth in juvenile and adult fishes is not expected to be impacted because these life stages have precise control over their internal ionic environment. Larval fishes, however, are more sensitive to the external environment and changes in the carbonate ion balance of the ocean might be sufficient to retarded skeletal development in early life. Experiments have shown that skeletal calcification of some invertebrates can be retarded at CO_2 concentrations well within those predicted to exist by 2100[161]. Whether these levels will have impacts on the skeletal development of larval fish is currently unknown.

12.2.3 Changes in ocean circulation

Oceanic, wind-driven and tidal currents contribute to the complex patterns of water flow on the GBR. The south flowing East Australian Current (EAC) and the north flowing Hiri Current are the dominant large-scale oceanographic features of the GBR. These currents form and diverge where the South Equatorial Current meets the Australian continental shelf at about 14°S. The EAC and Hiri currents influence the transportation of heat and nutrients throughout the GBR and the location and intensity of upwelling along the shelf break. Inshore, a northward flowing current runs along the coast, primarily driven by the south-easterly trade winds. In contrast, tides tend to drive water across the shelf. These opposing currents set up complex spatial and temporal patterns of water movement within the GBR lagoon.

Changes to current patterns on the GBR could impact fishes in several ways. First, local- and meso-scale currents appear to play an important role in the retention and dispersal patterns of larval fishes on the GBR[81,26]. Any changes in the strength or direction of these currents could influence larval transport among reefs. Second, circulation patterns influence the production and distribution of plankton[65] (McKinnon et al. chapter 6), which is food for larval and adult fishes. Changes to productivity brought about by the effect of climate change on oceanographic circulation could influence: i) the growth and survival of larval fishes; ii) the growth and distribution of pelagic fishes; and iii) the growth and reproductive success of reef-associated fishes, especially plankton feeders such as caesionids and many pomacentrids, and acanthurids.

The EAC generates areas of upwelling along the GBR shelf break, which results in the injection of nutrient rich water into the GBR lagoon at various locations. Some climate change models predict a general strengthening of the EAC, especially at high latitudes[27]. If these effects extend to lower latitudes we might expect to see impacts on the location, duration or intensity of upwelling along the GBR shelf break. This could periodically increase productivity in some areas and reduce productivity in others (Steinberg chapter 3), with correspondingly positive or negative effects on fishes in these areas. An increase in the strength of the EAC could also influence the migratory patterns of pelagic fishes, especially those that follow the warm summer EAC into southern waters[87].

Planktonic productivity on the GBR is influenced by periodic events that alter nutrient availability, such as freshwater inputs, sediment resuspension from tropical storms, and upwelling of nutrient rich water along the continental slope (McKinnon et al. chapter 6). These events are most pronounced during the summer monsoon, which is also the peak period for fish recruitment on the GBR[47,45,140]. Clearly, any impacts on oceanographic conditions that affect planktonic productivity during this time could have serious ramifications for the growth and survival of larval fishes and their subsequent recruitment to the adult population. Some (but not all) climate models predict a trend towards more El Niño like conditions over the next century[128], which would likely mean a weakened monsoonal influence. This might have a tendency to reduce nutrient enhancing events on the GBR, with potential flow-on effects to productivity. Despite the critical importance of currents and upwelling to the function of the GBR, predictions about the effects of climate change on oceanographic conditions remain highly uncertain and speculative.

Changes to major current patterns elsewhere in the world could also affect the GBR. The global meridional overturning circulation is one of the Earth's major mechanisms of heat transport from the tropics to the poles. It operates through the sinking of cold dense water near the poles and the return of warm surface water from the tropics[73,25]. A reduction in the formation of sea ice at the poles and/or influx of freshwater from the melting of icepacks and glaciers could slow the overturning circulation, with potential impacts at both high and low latitudes. Slowing of the Atlantic meridional overturning circulation has already been reported[25] and this could reduce the rate of warming in the north Atlantic. What impact it might have in the southern hemisphere is unclear, in part because this region is strongly influenced by overturning circulation around Antarctica[128,6]. The likelihood of a complete breakdown of overturning circulation remains highly uncertain[167,94]; however, if it was to occur it could lead to additional warming of tropical ocean water and a more rapid realisation of the issues associated with elevated temperature discussed above.

12.2.4 Changes in light and ultraviolet radiation

Eggs and larval stages of marine fishes are highly sensitive to ultraviolet (UV) radiation[188]. These life history stages will almost certainly experience greater mortality if UVB radiation levels increase as a result of climate change. Increased UVB radiation could also have an indirect effect on the growth and mortality of larval fishes due to negative impacts on the planktonic organisms that form the diet of larval fishes. In one of the few studies to have considered the link between solar radiation and the physical condition of larval reef fishes, Bergenius et al.[13] found that the growth rate of larval surgeonfish *Acanthurus chirurgus* was negatively associated with increasing levels of solar radiation. However, the predictions are that climate change will not significantly affect UV radiation levels in the GBR region and exposure to this threat is therefore low.

12.2.5 Sea level rise

Nearshore species will be exposed to coastal inundation and associated habitat changes as a result of the predicted 0.1 to 0.9 metre rise in sea level by 2100. Many coastal environments such as mangroves[139] and seagrass beds[119] have important nursery roles, providing juvenile fish with protection[18] or food resources[159]. Consequently, changes in the extent, relative area and proximity of the various habitat types will impact on nursery ground function. The direction of this impact is

likely to vary spatially, determined by the details of specific habitat change, and is likely to be different for particular species, depending on their specific requirements. Juveniles often utilise a mosaic of habitats, particularly in accessing intermittently available intertidal habitats[157], meaning the range of effects of changes in habitat availability will be complex and difficult to predict.

Sea level rise will influence connectivity among meso-scale habitat units such as estuaries, estuarine wetlands and freshwater habitats[160], changing the ability of fish like barramundi, *Lates calcarifer*, to access crucial juvenile habitats[149]. Sea level rise might be expected to enhance connectivity between habitats that are normally isolated at low tide. However, in many cases human responses to mitigate the threat of sea level rise, such as the construction of weirs and other barriers[77], are likely to reduce connectivity. This is a substantial threat to species that require access to wetland habitats since access is already impaired due to past human activities[77,160].

12.2.6 Physical disturbance – tropical storms

The frequency of intense cyclones is predicted to increase as a result of climate change[175], although there is still considerable uncertainty about the magnitude of increase that is likely to occur[93]. Tropical cyclones often cause a temporary decline in the abundance of some fishes on impacted reefs[62]. These declines can lag behind the initial impact and are likely due to the loss of critical habitat or food for certain species[184]. Recovery of fish populations occurs as benthic habitat recovers over a period of years to decades[62]. More frequent and larger cyclones will increase the disturbance regime experienced by reef communities, with increased impacts on fish communities at a local scale. A more troubling consequence of increased cyclone activity is the interaction with other disturbances, such as coral bleaching, that also decrease coral cover and degrade habitat structure. The cumulative effect of an increasing number of large-scale disturbances on the physical structure of reefs has the potential to seriously degrade fish communities on the GBR.

12.2.7 Rainfall and river flood plumes

Climate change models predict that rainfall patterns will become more extreme by 2100. Consequently, patterns of freshwater input to the GBR lagoon should also become more extreme, although predictions about the magnitude of these changes remain uncertain. Increased peaks in freshwater flow might periodically increase coastal productivity as a result of enhanced nutrient supply in the GBR lagoon. However, any increase will likely be relatively small because the majority of nutrients in the GBR lagoon are made available by resuspension of sediments, not riverine inputs[51]. In addition, increased productivity will be largely confined to coastal waters because flood plumes on the GBR mostly travel alongshore and rarely extend more than 10 to 20 km from the coast[52] (McKinnon et al. chapter 6).

Changes in rainfall and freshwater input are likely to impact species relying on access to wetland habitats. The ability of marine fish to access wetland habitat is influenced by both major flooding and localised flooding from storms[160], as well as by tides. A decrease in the frequency or volume of flooding at either scale will lead to less regular and less extensive connectivity. This could impair the viability of wetland habitats in many areas of the dry tropics, and move some wet tropics wetlands towards the intermittent connectivity currently a feature of the dry tropics.

Beyond direct effects on the ability to access wetlands, any reduction in the amount or regularity of rainfall will impact the viability of wetland pools as fish habitat and nurseries. Estuarine wetland pools range from fully fresh to hypersaline, depending on connectivity patterns[160]. Pools with irregular marine connections undergo a cycle of filling and drying in response to freshwater flows. Extended drought allows freshwater pools to dry or saline pools to develop extremely hypersaline conditions[160]. In either case their function as fish habitats is significantly altered. This is a far-reaching problem because altered rainfall patterns will not only affect the viability of individual pools, it will also reduce the total number of pools available, which have already been reduced by the construction of weirs and pasture ponding[77].

12.3 Impacts of climate change on population and communities

Impacts of climate change on fishes will be a combination of direct (eg effect of temperature on physiological processes) and indirect effects (eg impact of coral bleaching on habitat structure). These different effects will interact to influence the life histories, population dynamics, community structure and distributions of fishes on the GBR (Figure 12.1).

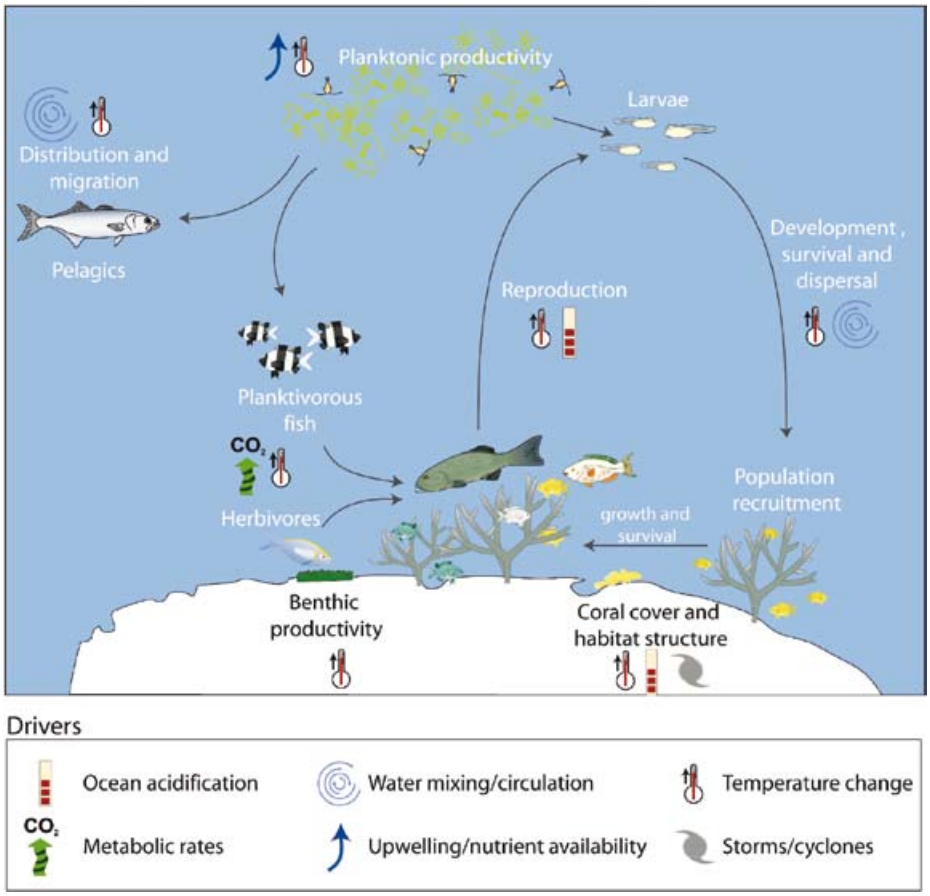
12.3.1 Life histories

Changes to the life history patterns of fishes are expected to occur based on permanently elevated sea temperature. Based on variation in life history traits of some tropical reef fishes across temperature gradients we might expect increased sea temperature to generally shift life histories towards: i) smaller maximum size; ii) reduced maximum longevity; iii) earlier maturation; and iv) longer breeding season. These shifts would be observed as long-term trends in mean values for populations at any given location.

Life history traits of reef fishes can differ markedly between populations and much of this variability appears to be influenced by complex interactions between temperature, density, food availability and mortality rates[109,60,33,141,150]. Within-species variations in maximum size and age have been correlated with temperature at geographical[33,141] and local scales[150]. In general, individuals tend to reach smaller maximum sizes and die younger in warmer environments, although there are a number of exceptions to this pattern (eg Kritzer[90], Williams et al.[177]). Age or size at maturation of fishes is often correlated with maximum age or size[17]. Therefore, we expect that the average size or age at maturation will also tend to decrease in populations that experience a shift towards smaller maximum size and younger average age at higher temperatures. Fishes on equatorial coral reefs currently have longer breeding seasons than those on the GBR[164]. Therefore, it is likely that breeding seasons will get longer at higher latitudes, as temperatures gradually increase.

The impact of increased temperature on growth rate is much more difficult to predict because it is highly dependent on food supply. Increased temperature might be expected to increase growth rate within populations (provided they are not already at their thermal optimum), but will only do so if more food can be consumed at higher temperatures. Indeed, some coral reef fishes exhibit an inverse relationship between growth rate and temperature across their geographic ranges[141]. For other species, a smaller size-at-age of individuals at warmer locations is also suggestive of a slower overall growth rate at higher temperatures[33]. At least some of this geographical variation in growth rates

Figure 12.1 *Representation of the ways climate change can influence fish populations and communities through a range of direct and indirect effects on different life stages*[a]



is likely caused by differences in food availability, nutritional quality, and population density among locations. The inverse relationship between temperature and growth for some reef-based populations contrasts with the evidence for increased growth rate at higher temperatures for larval fishes[105,183,110]. Consequently, it is possible that higher temperatures will tend to have a positive effect on the growth rate of larvae, but a negative effect on the growth rate of juveniles and adults.

There is already considerable variation in life history and demographic traits of reef fishes across habitat zones on the GBR. For example, parrotfishes on the outer barrier reef grow slower, have higher mortality rates, reach smaller maximum sizes and change sex earlier than individuals of the same species living just 10 to 20 km away on the mid-shelf[61,59]. Fishing pressure also causes variation

a Depends on multiple interactions between the physical environment, metabolic and behavioural responses of larvae and adults, energy transfer between trophic levels, and the effect of habitat structure on ecological interactions.

in the life history traits of exploited species among reefs[2,8]. Consequently, expected changes to life history traits as a result of a 1 to 3°C rise in sea temperature are not expected to be large compared to the natural variation that already exists among populations occupying different parts of the reef, or between fished and unfished populations.

12.3.2 Population dynamics

Large-scale population dynamics of many pelagic and non-reef marine fishes appear to be driven by fluctuations in the physical environment. Year class strength of several important fisheries species in the northeast Pacific have been linked to variation in temperature and oceanographic conditions over years to decades[72]. Multi-decadal cycles of sardine and anchovy abundances are correlated with fluctuation in temperature and productivity[30] and increases in horse mackerel abundance in the North Sea are correlated with increased temperature and higher plankton abundance, possibly driven by changes in currents[138]. These examples demonstrate that complex interactions between atmospheric forcing, hydrographic fluxes and productivity can affect the population dynamics of marine fishes.

In the tropical Pacific Ocean, population dynamics of tuna species (eg skipjack, *Katsuwonus pelamis*; yellowfin *Thunnus albacares* and bigeye, *Thunnus obesus*) fluctuate on multi-year cycles associated with the presence or absence of warm El Niño conditions[95,102,130]. Where the underlying causes of these fluctuations have been determined, it seems that changes in the distribution and abundance of smaller prey fish are largely responsible[129]. Small planktivorous fishes, which are the prey of tunas, shift their distributions in accordance with changes in the location of highly productive upwelling and convergence zones during El Niño events[95,30,130]. The tight coupling between temperature, hydrology and productivity indicates that any changes to oceanographic conditions in the tropical western Pacific as a result of climate change could influence the abundance of pelagic fishes in the GBR region. This notion is supported by the observation that black marlin, *Makaira indica*, seem to be more abundant off the Queensland coast during warm El Niño years and blue marlin, *Makaira mazara*, more abundant during cooler years[180]. In general, however, predictions about how climate change will affect oceanographic conditions currently lack sufficient certainty to assess the consequences for pelagic fishes on the GBR.

Reef fish abundances fluctuate based on variation in the supply of new recruits to the population and the effects that predation, competition and disturbance have on the survival of recruits after they join the reef-based population[83,28,46]. The most significant impacts of any changes to oceanographic conditions on the abundance of reef-associated fishes will likely come through effects on the growth, survival and dispersal of larvae. Wilson and Meekan[183] found that the magnitude of recruitment to bicolor damselfish, *Stegastes partitus*, populations in San Blas was positively correlated with larval growth, with large recruitment pulses containing the fastest growing larvae. Growth rate of larvae was positively correlated with water temperature and wind speed, both of which are likely to affect food availability or feeding efficiency of larval fishes[38]. Larger and better conditioned larvae are also more likely to survive after they settle to the reef[84]. Consequently, it seems that changes to pelagic productivity within the GBR lagoon, or feeding efficiency of reef fish larvae, could influence the replenishment of reef fish populations. Indeed, one recent study[31] found synchronised increases in the population size of damselfish species on the GBR following warm El Niño conditions, which suggests that altered conditions improved the survival of larval and juvenile fishes during the warmer period.

Currents and tides potentially play an important role in the retention and dispersal of larval fishes on the GBR[81,26]. Clearly, any changes to circulation patterns as a result of climate change could have fundamental effects on the spatial and temporal patterns of larval supply to individual reefs and the degree of connectivity among reefs. Changes to circulation patterns could also interact with changes to productivity to affect how many larvae survive the pelagic stage and their condition at settlement (Figure 12.1). For example, strong year classes of several damselfishes in the Galápagos Islands are correlated with warm El Niño events[109], suggesting that changed oceanographic conditions in these years improved their pre- and post-settlement survival. Increased sea temperature could also modify connectivity between reefs through affects on larval development and behaviour. Theoretical models predict that the spatial scale of larval dispersal is highly sensitive to the ontogenetic timing of reef-seeking behaviour and active swimming ability[4,39]. Therefore, the scale of dispersal between reefs might be reduced if larval development and swimming ability is accelerated in warmer conditions.

Overall, the uncertainty of how climate change will affect oceanographic conditions on the GBR, and our lack of understanding of how larvae will respond to changes in the physical environment, prevent us from making robust predictions about the consequences of climate change to the dynamics of reef fish populations. All we can say is that there is the potential for significant and widespread impacts.

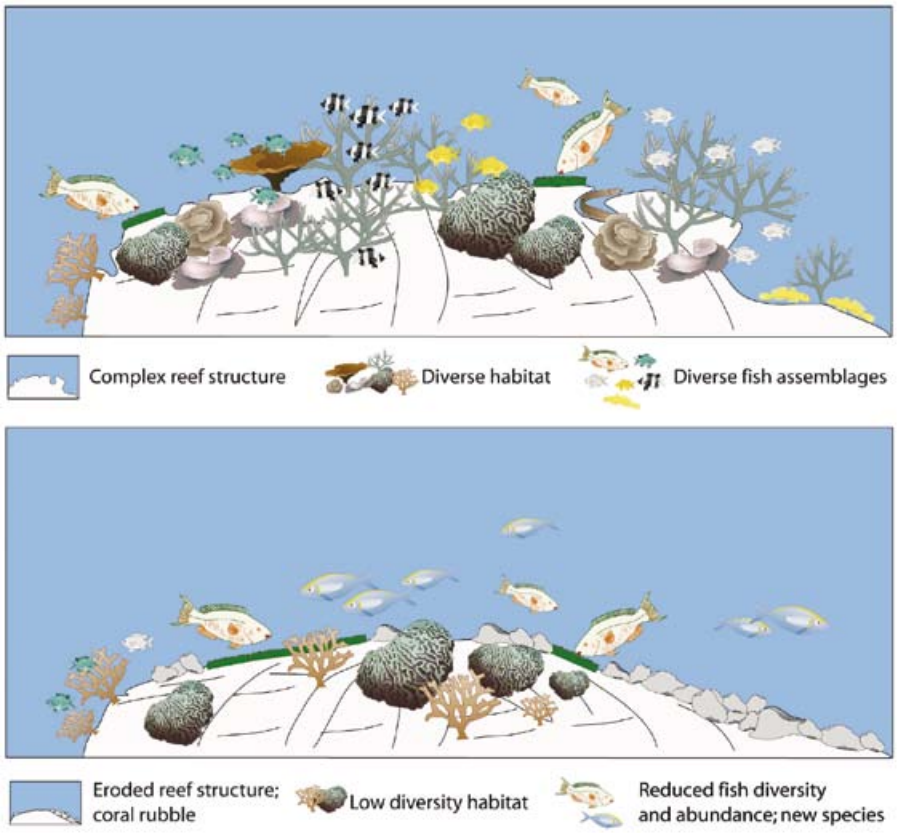
12.3.3 Community structure

The frequency of coral bleaching on the GBR is predicted to increase as sea temperature rises[68,75]. Regular bleaching of large areas of the GBR will change the composition of benthic reef communities and lead to fundamental shifts in the composition of the associated fish communities. Declines in live coral cover, changes in the species composition of remaining corals, and a loss of habitat complexity will all combine to decrease the diversity and abundance of reef fish assemblages and alter their species composition[114] (Figure 12.2).

Some reef fishes are obligate coral dwellers[116,53], some feed on live coral tissue[132] and many others preferentially settle into live coral[21,122,71]. These species are the ones most immediately affected by declining coral cover[89,163,113,184]. However, the majority of fishes associated with coral reefs are not directly dependent upon living corals. Based on current knowledge, we estimate the proportion of species that are coral dependent in reef fish communities on the GBR to be slightly less than 10 percent (or 107 of 1220 species listed in Randall et al.[137], a figure similar to elsewhere in the Indo-Pacific[85]. Some reef fish families are more reliant on corals than others, with a higher proportion of species in diverse reef fish families such as butterflyfish (Chaetodontidae), cardinalfish (Apogonidae) and gobies (Gobiidae) directly at risk from loss of corals (Figure 12.3). There is also a potential threat to higher taxonomic levels of reef fish biodiversity, with all species of some specialised genera (eg *Gobiodon, Paragobiodon*) and an entire family of reef fishes, the crouchers (Caracanthidae – represented by only two species) highly dependent upon corals. Many of these fish-coral relationships are species-specific and so the magnitude of the threat depends on the susceptibility of particular coral species to bleaching, combined with the degree of coral-specialisation of the fish species[113].

Although only one in ten coral reef fishes are directly coral-dependant, community responses to loss of coral cover extend to a greater range of species. Jones et al.[85] documented a dramatic decline in diversity of reef fish species on coastal reefs in Papua New Guinea following a severe loss of live coral

Figure 12.2 *Continued degradation of reef habitats has implications for diversity, abundance and community structure of reef fish assemblages*[b]

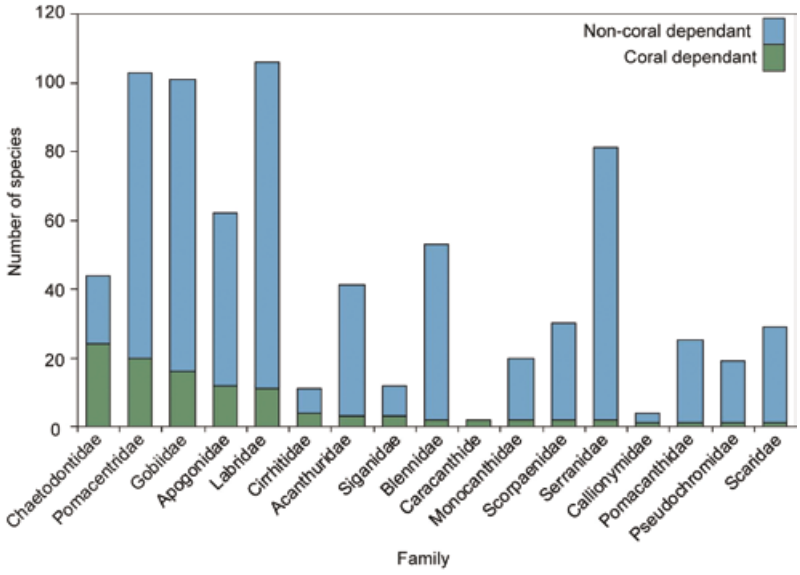


(coral cover declined from approximately 66 to 7%). Seventy five percent of fish species declined in abundance, with 50 percent of species declining by more than 50 percent, and only a relatively small number of species increased in abundance. This response to declining coral cover does not appear to be particularly unusual. In a recent meta-analysis, Wilson et al.[184] found that an average of 62 percent of reef fish species declined in abundance following a loss of at least 10 percent coral cover, and 29 percent of these species exhibited a decline in all the studies included. Declines in abundance were greatest among coral-dwellers and coral feeders, however, some invertebrate feeders and planktivores also declined in abundance.

Many reef fishes preferentially settle near live coral[85], even if adults are not coral dependent. This might be one of the reasons why a broad range of species exhibit a response to large-scale coral loss. A general degradation of habitat, and perhaps a suppression of settlement cues, could also contribute

b Loss of coral cover and structural complexity causes a gradual loss of species richness, reduced abundances, and a shift towards communities containing more generalist and fewer specialist species.

Figure 12.3 *Families of fishes on the GBR with one or more coral-dependent species*[c]



to a decline in settlement following bleaching. For example, recruitment of three species of common damselfish at One Tree Island declined following the 1998 bleaching event, even though only one of these species recruits to live coral[20]. This indicates that negative impacts of habitat degradation on coral reefs are not necessarily restricted to species that have an intimate association with living coral and that the permanent loss of coral cover can have far-reaching effects on the composition of reef fish communities. The species most likely to benefit from coral loss and reef degradation are some of the small generalist species and herbivores that live in areas of low relief and rubble, such as various gobies, blennies and damselfishes[168,10].

The changes so far detected within fish assemblages in response to declining coral cover might not give a complete picture of the long term impacts of coral loss because population declines may take years to emerge, especially for long lived species. Declines in the abundance of obligate coral feeding butterflyfish at Trunk Reef, GBR, following a catastrophic loss of live coral (greater than 90% decline) took over two years to become apparent[134]. This indicates that adults of some coral dependent species are able to persist for a considerable time following a loss of coral habitat or food. Rather than immediate responses to coral loss, we might often see slow population declines due to increased attrition of adults and reduced replenishment by recruits. Loss of coral can have serious effects on the growth[89] and body condition[133] of corallivorous species, which will likely flow on to the reproductive success of the population. Therefore, the negative effects of habitat loss on the survival of adults and the availability of substratum for the settlement of new recruits might also be reinforced by a general decline in the abundance of larvae to replenish local populations.

c The number of species estimated to be coral dependent (green) is shown as a component of the total number of species listed for each family in Randall et al.[137] (blue).

The diversity of reef fish communities is often correlated with habitat structure[83,168]. Reefs with high structural complexity support more individuals and more species than reefs with low structural complexity. Many of the corals most susceptible to coral bleaching are also the ones with the highest structural complexity[107]. Loss of these coral species will reduce habitat complexity on reefs. Continued bleaching will cause further loss of structural complexity through erosion of the reef matrix as coral recruitment and growth struggles to keep pace with coral mortality. If the frequency of bleaching increases as predicted, we can expect an overall decline in the structural complexity of coral reefs on the GBR, with a corresponding decline in the diversity and abundance of the associated fish communities[100,56] (Figure 12.2). Herbivores often increase in abundance following a loss of coral cover[184], presumably because more area becomes available for algal growth following coral bleaching, however, even these species ultimately decline as habitat structure is lost[154,54].

Recent studies indicate that fish communities on the GBR have considerable resilience to disturbance and can recover from cyclones and bleaching events over years to decades, provided that benthic habitat recovers[62]. Elsewhere, where not all coral species have recovered, the recovery of fish communities has also been incomplete[15] or there have been phase shifts to communities with fewer coral specialists and more habitat generalists[10]. The consequences of habitat loss on GBR fish communities will depend on the frequency and intensity of bleaching events, combined with the impacts of other disturbances, relative to the potential for the reefs and their associated fish communities to rebound. Fish communities on inshore reefs are at greatest risk because these reefs are often the ones most impacted by coral bleaching[14] and have greater exposure to the effects of sedimentation and pollution from terrestrial sources. Fish species that are not directly associated with coral reefs, such as many coastal, inter-reef and pelagic species are less likely to be impacted by the loss of reef habitat.

12.3.3 Distributions and range shifts

Biogeographic range shifts are one of the clearest signatures of climate change impacts in animal communities[125]. Range shifts towards higher latitudes, correlated with higher than average ocean temperature, have been observed in a substantial number of temperate marine fishes. For example, a change in the structure of the nearshore fish community in the Southern California Bight from one dominated by northern (cold affinity) species to one dominated by southern (warm affinity) species corresponded with a rapid increase in mean sea surface temperature of approximately 1°C in 1996 to 1997[70]. A similar increase in mean sea surface temperature appears to explain the northward shift in the range of 13 species of marine fishes in the North Sea between 1977 and 2001[127] and a 1 to 6°C elevation in sea temperature was associated with the appearance of 29 new species of tropical fishes off the coast of North Carolina[124].

Most species of fish on the GBR are cosmopolitan in distribution. However, a considerable number of species appear to have distributions concentrated in the northern half of the GBR (see Table 12.1 for examples). A smaller number of species have distributions limited to the southern half of the GBR (see Table 12.2 for examples). Changes in the distributional extent or relative abundance of fishes on the GBR will almost certainly occur as a result of the predicted 1 to 3°C increase in mean sea temperature by 2100. Warming is predicted to be greater in the southern half of the GBR compared to the northern half (Lough chapter 2). Over 90 species of fishes from the northern half of the GBR do

not currently occur, or are relatively uncommon, in the southern or far-southern regions of the GBR (Table 12.1). Some of these species will expand their southern limits as temperature increases. Few changes are likely to the northern range limits of fishes already resident on the northern half of the GBR because the magnitude of temperature changes will be smaller and many of these species have ranges that extend into equatorial regions, where the mean ocean temperature is already warmer than that currently experienced on the GBR. The Whitsunday region appears to be an important biogeographic boundary for many northern range GBR fishes (M Emslie pers comm) and we expect that range extension will mostly be south of this region.

Table 12.1 *Some GBR fish species restricted to, or most abundant on, the northern half of the Great Barrier Reef (Derived from Russell[148], Kuiter[92], Randall et al.[137] and Randall[136])*

Family	Species	Common Name	Distribution
Pomacanthidae	*Centropyge aurantia*	Golden Angelfish	Northern GBR
	Centropyge loriculus	Flame Angelfish	Northern GBR
	Centropyge multifasciata	Multi-barred Angelfish	Northern GBR
	Geniacanthus lamarck	Lamarck's Angelfish	Northern GBR
	Pomacanthus navarchus	Blue-girdled Angelfish	Northern GBR*
	Pomacanthus xanthometopon	Blueface Angelfish	Northern GBR
Chaetodontidae	*Chaetodon rafflesi*	Latticed Butterflyfish	Northern GBR*
	Chaetodon ocellicaudus	Spot-tail Butterflyfish	Northern GBR
	Chaetodon reticulatus	Reticulate Butterflyfish	Northern GBR*
	Chaetodon semeion	Dotted Butterflyfish	Northern GBR
Pomacentridae	*Amblypomacentrus breviceps*	Black-banded Damsel	Northern GBR*
	Cheiloprion labiatus	Big-lip Damsel	Northern GBR
	Chromis delta	Deep-reef Puller	Northern GBR
	Chromis xanthochira	Yellow-axil Puller	Northeastern Australia
	Dascyllus melanurus	Black-tailed Humbug	Northeastern Australia
	Lepidozygus tapeinosoma	Fusilier Damsel	Northern Australia*
	Neopomacentrus cyanomos	Regal Demoiselle	Northern Australia*
	Pomacentrus adelus	Obscure Damsel	Northern Australia
	Pomacentrus nigromarginatus	Blackmargin Damselfish	Northern GBR
	Pomacentrus reidi	Grey Damsel	Northeastern Australia*
	Amphiprion chrysopterus	Orangefin Anenomefish	North Queensland*
	Amphiprion percula	Eastern Clown Anenomefish	North Queensland*
	Premnas biaculeatus	Spine-cheek Clownfish	North Queensland*
Holocentridae	*Myripristis adusta*	Shadowfin Soldierfish	Northern Australia
	Myripristis vittata	Whitetip Soldierfish	Northern Australia
	Neoniphon opercularis	Blackfin Squirrelfish	Northern Australia

Family	Species	Common Name	Distribution
	Sargocentron punctatissimum	Speckled Squirrelfish	Northern Australia
	Sargocentron spiniferum	Sabre Squirrelfish	Northern Australia*
	Sargocentron violaceum	Redface Squirrelfish	Northern Australia
Solenostomidae	*Doryrhamphus janssi*	Cleaner Pipefish	Northern Australia
	Doryrhamphus dactyli-ophorus	Banded Pipefish	Northern Australia
	Corythoichthys ocellatus	Ocellated Pipefish	Northern GBR
	Halicampus mataafe	Samoan Pipefish	Northern GBR
	Hippocampus bargibanti	Pygmy Seahorse	Northern GBR
Serranidae	*Pseudanthias dispar*	Fairy Basslet	Northern GBR
	Pseudanthias huchtii	Pacific Basslet	Northern GBR
	Pseudanthias lori	Lori's Basslet	Northern GBR
	Pseudanthias luzonensis	Luzon Basslet	Northern GBR
	Pseudanthias smithvanizi	Princess Basslet	Northern GBR
	Serranocirrhitus latus	Swallowtail Basslet	Northern GBR
	Luzonichthys waitei	Pygmy Basslet	Northern GBR
	Cephalopholis leopardus	Leopard Rockcod	Northern Australia*
	Gracilia albomarginata	White-square Cod	Northern GBR*
	Plectropomus laevis	Bluespotted Coral Trout	Northern GBR*
	Plectropomus oligocanthus	Vermicular Cod	Northern GBR
	Belonoperca chabanaudi	Arrowhead Soapfish	Northern GBR
	Liopropoma multilineatum	Yellow Reef Basslet	Northern Australia
Pseudochromidae	*Pseudochromis bitaeniatus*	Slender Dottyback	Northern GBR
	Pseudochromis flammicauda	Orangetail Dottyback	Northern GBR
Plesiopidae	*Assessor flavissimus*	Yellow Scissortail	Northern GBR
Apogonidae	*Ostorhinchus compressus*	Blue-eyed Cardinalfish	Northern Australia
	Ostorhinchus fragilis	Fragile Cardinalfish	Northern Australia
	Ostorhinchus hoeveni	Frostfin Cardinalfish	Northern Australia
	Ostorhinchus lateralis	Pinstripe Cardinalfish	Northern GBR
	Ostorhinchus sangiensis	Sangi Cardinalfish	Northern GBR
	Archamia zosterophora	Girdled Cardinalfish	Northern GBR
	Sphaeramia nematoptera	Pajama Cardinalfish	Northern Australia
Carangidae	*Alepes vari*	Herring Scad	Northern Australia
	Carangoides humerosus	Epaulette Trevally	Northern Australia*
	Carangoides plagiotaenia	Barcheck Trevally	Northern Australia
Lutjanidae	*Lutjanus bohar*	Red Bass	Northern Australia*
	Lutjanus decussatus	Checkered Snapper	Northern Australia
	Lutjanus ehrenbergii	Ehrenberg's Snapper	Northern Australia
	Lutjanus johnii	Golden Snapper	Northern Australia

Family	Species	Common Name	Distribution
	Lutjanus semicinctus	Blackbanned Snapper	Northern GBR
	Macolor macularis	Midnight Snapper	Northern Australia*
Lethrinidae	*Lethrinus harak*	Thumbprint Emperor	Northern Australia
	Lethrinus erythracanthus	Orangespotted Emperor	Northern Australia
Nemipteridae	*Scolopsis affinis*	Bridled Monocle Bream	Northern Australia*
	Scolopsis margaritifer	Pearly Monocle Bream	Northern Australia
Caesionidae	*Pterocaesio tile*	Neon Fusilier	Northern GBR
Scaridae	*Scarus japanensis*	Redtail Parrotfish	Northern GBR
	Scarus quoyi	Greenblotch Parrotfish	Northern GBR
Blenniidae	*Ecsenius australianus*	Australian Combtooth Blenny	Northern GBR
	Ecsenius midas	Midas Combtooth Blenny	Northern GBR
	Meiacanthus luteus	Yellow Fangblenny	Northern Australia
Gobiidae	*Amblyeleotris fontanesii*	Giant Shrimp Goby	Northern Australia
	Amblygobius bynoensis	Bynoe Goby	Northern Australia*
	Bryaninops natans	Purple-eyed Goby	Northern GBR
	Exyrias bellissimus	Mud-Reef Goby	Northern GBR
	Exyrias puntang	Puntang Goby	Northern GBR
	Eviota bifasciata	Twostripe Eviota	Northern GBR
	Eviota nigriventris	Red-and-black Eviota	Northern GBR
	Eviota pellucida	Neon Eviota	Northern GBR
	Nemateleotris decora	Purple Firegoby	Northern GBR
	Phyllogobius platycephalops	Flathead Sponge Goby	Northern GBR
	Trimma tevegae	Bluestripe Pygmygoby	Northern GBR
	Valenciennea randalli	Greenband Glider Goby	Northern GBR
Acanthuridae	*Ctenochaetus tominiensis*	Orange-tip Bristletooth	Northern GBR
	Naso thynnoides	OnespineUnicornfish	Northern GBR
	Naso caeruleacauda	Blue Unicornfish	Northern GBR
	Naso minor	Blackspine Unicornfish	Northern GBR
Siganidae	*Siganus javus*	Java Rabbitfish	Northern Australia
	Siganus punctatissimus	Spotted Rabbitfish	Northern GBR
Tetraodontidae	*Canthigaster papua*	Netted Toby	Northern GBR
Ostraciidae	*Ostracion solorensis*	Striped Boxfish	Northern GBR

* Less abundant, uncommon or rare on the southern GBR

Table 12.2 *Some GBR fish species restricted to, or more abundant on, the southern half of the Great Barrier Reef (Derived from Russell[148], Kuiter[92], Randall et al.[137] and Randall[136])*

Family	Species	Common Name	Distribution
Pomacanthidae	*Chaetodontoplus conspicillatus*	Conspicious Angelfish	Southern GBR and Coral Sea
	Chaetodontoplus meridithi	Yellowtail Angelfish	Southern GBR and NSW
Chaetodontidae	*Chaetodon geuntheri*	Gunther's Butterflyfish	Southern GRB and NSW
Pomacentridae	*Chromis nitida*	Yellowback Puller	Central and southern GBR
	Neoglyphidion polyacanthus	Multispine Damselfish	Southern GBR
	Parma polylepis	Banded Scalyfin	Southern GBR and NSW
	Pomacentrus australis	Australian Damsel	Southern GBR and NSW
Serranidae	*Epinephelus undulatostriatus*	Maori Rockcod	Southern GBR and NSW
	Pseudanthias pictilis	Painted Basslet	Southern GBR*
Aploactinidae	*Neoaploactis tridorsalis*	Threefin Velvetfish	Southern GBR
Pseudochromidae	*Ogilbyina novaehollindae*	Multicoloured Dottyback	Southern GBR
Plesiopidae	*Paraplesiops poweri*	Northern Blue Devil	Central and southern GBR
Apogonidae	*Archamia leai*	Lea's Cardinalfish	Southern GBR and Coral Sea
	Ostorhinchus flavus	Brassy Cardinalfish	Southern GBR
	Ostorhinchus capricornis	Capricorn Cardinalfish	Capricorn Group and south
Carangidae	*Seriola lalandi*	Yellowtail Kingfish	Southern Australia
Sparidae	*Pagrus auratus*	Snapper	Southern Australia
Lethrinidae	*Gymnocranius audleyi*	Collar Sea Bream	Southern GBR
	Lethrinus miniatus	Redthroat Emperor	South of 18 degrees
Pempheridae	*Pempheris analis*	Bronze Bullseye	Southern GBR
Cheilodactylidae	*Cheilodactylus vestitus*	Crested Morwong	Southern GBR and NSW
Labridae	*Anampses femininus*	Bluetail Wrasse	Southern GBR
	Choerodon venustus	Venus Tuskfish	Southern Queensland
	Coris aurilineata	Goldlined Wrasse	Southern GBR
	Cirrhilabris laboutei	Laboute's Wrasse	Southern GBR and Coral Sea*
	Macropharyngodon choati	Choat's Wrasse	Southern GBR*
	Pseudolabrus guentheri	Gunther's Wrasse	Southern GBR
	Suezichthys devisi	Australian Rainbow Wrasse	Southern GBR and NSW

Family	Species	Common Name	Distribution
Blenniidae	*Petroscirtes fallax*	Yellow Sabretooth Blenny	South of 17 degrees
	Cirripectes alboapicalis	Whitedotted Blenny	Southern GBR
	Stanulus talboti	Talbot's Blenny	Southern GBR
Gobiidae	*Istigobius hoesei*	Hoese's Sandgoby	Southern GBR and NSW
Acanthuridae	*Prionurus maculatus*	Spotted Sawtail	Southern GBR
	Prionurus microlepidota	Australian Sawtail	Southern GBR

* Less abundant on northern GBR

In contrast to range expansions by northern species, some species that are currently confined to the southern half of the GBR (Table 12.2) may become more geographically restricted as sea temperature increases. The latitudinal range of coral reefs is not expected to expand significantly in response to increasing sea temperature because coral growth is limited by light and carbonate alkalinity in addition to temperature[69]. Some southern GBR species are confined to coral reefs and are unlikely to persist in non-reef areas, even if temperatures become more favourable at higher latitudes. Consequently, contracting northern range limits of these species would not be matched by expanding habitat at the southern end of their ranges. The smaller ranges of fishes restricted to the southern and far southern GBR would ultimately increase their risk of extinction from other impacts.

Seasonal transport of coral reef fish larvae into temperate regions by the EAC is a regular occurrence[22]. The frequency of these incursions, and the number of species arriving in southern locations, could increase with increasing sea temperature and potential increases in the strength of the EAC at higher latitudes[27]. The ability of tropical species to establish permanent populations at higher latitudes will depend on their degree of dependence on coral reefs for food, shelter, and reproduction, their tolerance to lower minimum temperatures in winter, and competition from established sub-tropical and temperate water species. Some species of fishes common on coral reefs already have populations beyond the latitudinal extent of coral reef (eg neon damselfish, *Pomacentrus coelestris*; banded goby, *Amblygobius phalaena*; yellowtail fang blenny, *Meiacanthus atrodorsalis*; yellowbar sandperch, *Parapercis xanthozona*; yellow-brown wrasse, *Thalassoma lutescens*; surge wrasse, *T. purpureum*; pennant coralfish, *Heniochus acuminatus*)[35,137] and these species will probably expand their southern range limits as sea temperature increases. However, the appearance of entire communities of coral reef fishes in locations much further south than their current distributions is unlikely within the next 50 to 100 years.

Interannual range limits of pelagic species frequently track ocean temperature[117,130]. Many of the larger pelagic species found in GBR waters, such as mackerel, tuna and marlin have components of their populations that migrate to higher latitudes in summer[87]. For these species, increased sea temperature is likely to result in an earlier timing of seasonal migrations and perhaps an extension of the southern limit of the migration.

12.4 Adaptive capacity

Heritable changes in seasonal life history events that correspond with climate change have already been detected in a number of terrestrial animals[23]. Changes in the timing of reproduction, length of the growing season, and the location of over wintering sites have all been found to involve genetic change. In each case, the phenotypic change corresponds to an increase in fitness under the new climate regime. This indicates that genetic adaptation to climate change is already underway in some animal populations.

Populations of fishes on the GBR experience seasonal variations in temperature greater than the 1 to 3°C increases predicted for the GBR. Many reef fishes also have very large geographic ranges, covering a temperature gradient larger than the predicted change. Importantly, some species also have populations extending into equatorial regions where the maximum temperature is already similar to that predicted to occur on the southern half of the GBR by the end of the century. These observations indicate that most GBR fishes could accommodate relatively small increases in sea temperature, either as a result of phenotypic plasticity (acclimation) of resident populations, or gene flow from more northern populations.

There is evidence for strong genetic connectivity among populations of fishes on the GBR[48,111,7]. This has two consequences. First, southern populations might already contain considerable tolerance to higher temperatures due to regular genetic input from northern populations. Second, gene flow from northern populations might assist southern populations to adapt to increasing temperatures in the future. The potential for genetic adaptation will also depend on generation time. Many coral reef fishes are long lived (eg 40 plus years for some acanthurids, serranids and lutjanids[33,126]) and there is little hope of genetic adaptation in local populations of these species within the next 50 to 100 years unless there is substantial genetic input from populations that already inhabit warmer waters. The short generation times of some smaller species, however, might enable local genetic adaptation to occur. For example, many goby species are annuals[66,43], which means there is an opportunity for selection to occur over 50 to 100 generations before the end of the century.

Although acclimation or adaptation to increased temperature seems possible, especially for short-lived species, there is little prospect of adaptation to habitat degradation. Some reef fishes depend on live coral at one or more critical life stages[85]. Many more require complex habitat structure to escape predators[16,168,3]. Significant declines in fish diversity following large-scale loss of live coral[184] and further declines following loss of habitat structure[54,56] indicate that many species are unable to persist once their habitat has seriously degraded. There is little prospect of genetic adaptation under these circumstances. Habitat degradation will also retard genetic adaptation to other climate change impacts (eg increased temperature) by reducing genetic variability within populations (decreased population size) and by reducing genetic connectivity between populations (smaller and more patchily distributed populations).

The consequences of strong genetic selection to climate change impacts are largely unknown. One potential problem is that intense selection to one environmental factor (eg temperature) could reduce the genetic capacity to adapt to other environmental changes[86]. Unfortunately, our understanding of genetic adaptation in tropical marine fishes is at such a rudimentary stage that it is difficult to predict the long-term genetic consequences of climate change on GBR fish populations.

12.5 Linkages and fisheries implications

The different impacts of climate change will interact with each other and with other threats and stressors to coral reefs, potentially leading to synergistic or cumulative effects that exacerbate the problem. For example, increased bleaching and increased cyclone disturbance will have cumulative effects on the degradation of coral reef habitat. These impacts could interact with terrestrial pollution to further degrade benthic communities, or even cause a regime shift from coral to algal dominated reefs. Although certain reef fish may play a key role in maintaining coral reef functions[9], the majority of fish species are likely to respond to coral reef regime shifts rather than being the cause of them. A regime shift on GBR coral reefs will almost certainly cause a loss of diversity, especially among coral dependent species, and a shift towards communities containing fewer specialist and more generalist species[113,10]. While the loss of species in high diversity communities may have little impact on the ecosystem as a whole, the shear number of species that are potentially threatened is cause for concern.

The long-term implications of predicted changes to fish populations and communities for ecosystem processes are a matter for speculation only. Given the likely links between biodiversity and ecosystem processes such as productivity (eg Tilman[169], Loreau[101]), it is possible that a decline in reef fish biodiversity will lead to a reduction in energy transfer to higher trophic levels, which may mean that with climate change, reefs will support a reduced biomass of higher order predators. However, changes to primary productivity in plankton and on the reef are likely to be of greater significance. Changes to primary and secondary productivity brought about by climate change could flow on to species at high trophic levels (Figure 12.1), some of which are important fisheries species (eg coral trout). However, no clear predictions can be made about how trophic structure and biomass might be affected, because the net impact of climate change on productivity is highly uncertain and is likely to vary from place to place – there might be positive effects on biomass in some locations and negative effects in others.

It is generally accepted that climate change has had, and will continue to have, profound impacts on the distribution and productivity of the worlds' fisheries[106]. Numerous studies have demonstrated a strong link between climatic changes, such as El Niño and La Niña events, and the distribution or productivity of exploited fish populations[95,121,187,123]. However, these impacts tend to be species or fisheries-specific[96], making it difficult to predict the magnitude and direction of changes in fisheries productivity arising from environmental change. The consensus is that while some fisheries will be negatively impacted by climate change, others may benefit[106].

Compared with many other fisheries around the world, fisheries in the GBR region are generally well managed and are not considered overexploited[182,41,42]. Climate change will almost certainly have some impact on the productivity of GBR fisheries, with implications for sustainable harvest levels. However, predicting the relative importance of these impacts is extremely difficult, because of uncertainty in climate change predictions for the region, the wide range of possible effects of climate change on fish population dynamics, life histories and distribution, and the confounding effects of fishing. Nevertheless, it is clear that climate change can exacerbate population declines or hinder recovery of stocks that are already overfished[186]. This increases the importance of ensuring that fish stocks in the GBR are not over exploited as they are forced to deal with climate change over the next 50 to 100 years.

One area of concern for fisheries productivity is the potential for climate change to affect the relationship between stock size and recruitment. Changes to ocean circulation, temperature, and productivity could potentially interact to change the survival and dispersal patterns of fish larvae. Fisheries productivity could decline if environmental changes result in fewer recruits reaching adult populations. A change in larval dispersal and survival may also result in reduced gene flow and a more fragmented stock structure, which could further reduce the sustainability of fish stocks. Unfortunately, we do not know enough about how climate change will affect larval survival and dispersal to predict if stock-recruitment relationships will be disrupted to the extent where fisheries productivity will be significantly impacted.

Variation in life history traits of exploited species has important implications for sustainability of fisheries[8,178]. Populations with different life histories may respond differently to similar levels of fishing pressure and, therefore, may require different management strategies. Given the prediction that increased temperature will result in a shift in life histories of some species towards smaller size, earlier maturation and reduced longevity, populations of exploited species might be expected to become less vulnerable to fishing pressure. However, the total population biomass may decline if food resources do not increase as temperature increases. Ultimately, local populations may tend towards faster population turnover, but with lower exploitable biomass.

Most species of commercial importance on the GBR are broadly distributed, and their distributions are not likely to be significantly affected by climate change in the short to medium term. However, one important commercial and recreational species, *Lethrinus miniatus* (sweetlip or redthroat emperor), has a restricted anti-equatorial distribution with an apparent upper thermal limit of about 28°C. On the GBR, *L. miniatus* is restricted to south of 18°S where the impact of climate change on water temperature is predicted to be greatest (Lough chapter 2). With a potential longevity of at least 20 years *L. miniatus* is unlikely to adapt quickly to environmental change[177]. Therefore, its distribution on the GBR will likely be reduced as water temperature increases. This will affect the distribution of fishing effort and potentially reduce fisheries productivity. A number of other exploited species in the GBR region exhibit seasonal (scombrids) or ontogenetic (lutjanids) movement patterns. These movement patterns may be affected by climate change through shifts in ocean currents, changes in prey availability, or behavioural responses to increased water temperature. Changes in movement patterns are likely to alter the distribution and timing of fishing effort, but alone are unlikely to significantly impact on fisheries productivity.

12.6 Summary and recommendations

12.6.1 Major vulnerabilities to climate change

Climate change will have significant impacts on fishes of the GBR. The most immediate and identifiable effects will be changes in the community composition of reef-associated species due to habitat degradation. Reef habitat will continue to degrade if the intensity and/or frequency of coral bleaching increases as predicted. Loss of coral cover will be exacerbated by increased physical disturbance from tropical storms and other stressors. There is now ample evidence that large-scale declines in coral cover can have serious consequences for the structure of reef fish assemblages. Coral-dependant fishes suffer the greatest declines in abundance as a result of coral loss. However,

some species that do not appear to have strong affiliations with live coral also decline in abundance following persistent loss of coral cover.

Population declines may take several years to become apparent because adults of many species can persist for a relatively long time in the absence of live coral. Reef fish diversity and abundance will be further compromised by loss of habitat structure. Unless benthic communities can recover between disturbances, there will be a steady decline in the structural complexity of the reef, with corresponding declines in the abundance of fishes that use the reef for shelter. Some species, such as territorial herbivores and invertebrate feeders, may initially increase in abundance as coral cover declines, but even these species will decrease in abundance if habitat structure erodes. Declines in species richness and abundance will be highly patchy, and interspersed with cycles of recovery, but the overall trend will be negative if climate change continues to cause severe and repeated impacts on the composition and physical structure of the reef benthos.

Range expansions and contractions of GBR fishes will likely occur as ocean temperature increases. Some northern range fish species will extend their southern distribution limits as temperature increases. A smaller number of southern range species will contract their northern distribution limits as temperatures increases. Some of these southern endemic species will face an increased risk of extinction from other threats as their ranges contract. Range extension and contractions are unlikely to have significant consequences for the productivity of most fisheries species. An exception is *Lethrinus miniatus* (sweetlip or redthroat emperor), which is expected to become more restricted to southern locations as temperature increases. The timing of seasonal migrations by pelagic species will likely shift to match the changed thermal regime. Whether the productivity of pelagic fisheries is impacted will largely depend on the effect that climate change has on ocean productivity and the abundance of smaller prey species.

Increased temperature will probably cause a shift in life history traits of local populations, although these changes will be relatively small compared to the natural variation already exhibited by many species across their geographic ranges. The most likely response to rising temperatures will be a shift in life history traits in southern populations to more closely match those currently seen in northerly locations. We predict there will be a trend towards populations of fishes breeding earlier, breeding over a longer period, and having reduced maximum size and longevities compared to current day populations.

Climate induced changes to oceanographic conditions could have far-reaching consequences for the growth, survival, and dispersal patterns of larval fishes, with important implications for the dynamics of adult populations[31]. However, predictions of how ocean currents and productivity patterns will change on the GBR over the next 50 to 100 years lack sufficient certainty to formulate conclusions about the impacts on fish populations. This is a critical gap in our knowledge of climate change impacts on the GBR.

Small increases in ocean temperature (1 to 2°C) may be beneficial for the supply of new recruits to adult populations. However, temperature changes at the upper range of climate change predictions (3 to 4°C) are likely to have negative effects on the reproductive performance of adults, especially if they are combined with the predicted extremes of ocean acidification. The overall conclusion is that small increases in temperature might not be harmful, and could even be beneficial to larval growth

and survival, but larger increases are likely to have significant consequences for the replenishment of fish populations. These predictions need to be weighed against the considerable stochastic variation that occurs in larval supply through time and space.

It seems likely that many fish species will acclimatise to increased sea temperature as a result of existing phenotypic plasticity in their populations. Connectivity between populations should promote genetic adaptation to temperature by gene flow from extant populations in warmer conditions. Genetic adaptation to climate change over the next 50 to 100 years will be most evident in small, short-lived species, where selection can operate over a large number of generations. Some reef fishes live for many decades and we do not expect to see strong genetic adaptation to changing climate over the next 50 to 100 years in these species, unless there is extensive gene flow from low latitude populations. There is little prospect of significant genetic adaptation to habitat degradation. Habitat loss could have a negative effect on the potential for adaptation to other environmental changes, because adaptation will be slower in populations that have been reduced in size and that have lower connectivity as a result of habitat degradation.

Throughout this review we have tried to provide a framework for understanding the likely consequences of climate change for fishes on the GBR. We stress that confidence in many of our conclusions is low because of: i) uncertainty in climate change projections; ii) poor understanding of the responses likely to accompany changes in environmental factors at individual, population and community levels; and iii) the complexity of interactions that can occur between the different physical and biological factors that will be affected by climate change and their interactions with other coral reef stressors.

12.6.2 Potential management responses

Although there is little prospect of controlling climate change in the short to medium future, linking management strategies that target other human impacts such as exploitation and sedimentation may increase the resilience of reef habitats[75]. Given the evidence for top-down control of coral reefs, maintaining healthy predator and herbivore fish populations may provide a certain amount of resilience to climatically induced changes. However, marine protected areas are not a 'catch-all' solution to the problems faced by coral reefs, and ultimately, they cannot protect biodiversity from extrinsic disturbances[19,85]. While marine protected areas can benefit exploited species when habitat is degraded, it must be recognised that the majority of small reef fish species are not exploited and are more likely to be influenced by habitat degradation than exploitation. Enhancing reef resilience by maintaining water quality and limiting disturbances that stress corals and degrade reef habitat will be critical for maintaining healthy assemblages of reef fishes.

There are formal management regimes in place for commercially targeted fish stocks on the GBR, making them relatively well protected compared to most other reef regions. It will be important to ensure stocks are well managed into the future to reduce the risk of fisheries collapses as the effects of climate change become more pronounced. Ensuring that GBR fisheries have fully implemented ecosystem-based fishery management regimes in line with recently developed national standards will be important for maintaining sustainable stocks and ensuring fisheries productivity. Integrating potential impacts of climate change into this framework is a critical next step. Incorporating a 'safety

margin' into harvest levels could also provide some insurance in the face of uncertainty about the impacts of climate change. Consideration should also be given to the possibility that reduced planktonic productivity and loss of benthic shelter could lead to a reduction in food supply for pelagic and reef-based fisheries species. Harvest levels may need to be adjusted if there are substantial reductions in the abundance of smaller prey species.

Mangroves, estuaries and wetlands are important nursery and juvenile habitats for some GBR fishes. These habitats are under increasing threat from terrestrial development in addition to the potential impacts associated with climate change, and require additional protection to prevent their continued loss or degradation. The consequences of installing barriers to mitigate sea level rise needs to be considered carefully because these devices can restrict key ontogenetic movements of fish between coastal wetlands, estuaries and the sea.

12.6.3 Further research

A great deal more research is required before we can predict the full ramifications of climate change for fishes on the GBR. More information is required on the effects that changes in the physical environment (eg temperature and pH) will have on the function and behaviour of reef fishes. Nearly all the available data on how fishes respond to changes in these environmental factors comes from temperate species and these results might not be directly applicable to tropical marine fishes. Improved projections of how productivity on the GBR will change as a result of climate change will also be critical for understanding how individual performance and population dynamics will respond to changes in the physical environment.

Regional models of ocean circulation on the GBR under various climate change scenarios are required to assess the impacts of climate change on dispersal patterns of marine animals, including fishes. Oceanographic models will also be critical for predicting the spatial and temporal patterns of planktonic productivity on the GBR under different climate change scenarios. Once we have these predictions, we also need reliable estimates of the scales of dispersal and retention exhibited by fish larvae on the GBR. Only then can models be parameterised with meaningful estimates of larval growth, survival and dispersal, and applied in sensitivity analyses to assess the potential impact of climate change on the replenishment of adult populations.

More information is needed on the habitat requirements of reef fishes, especially around the time of settlement. Many reef fishes are closely associated with live coral habitat at the time of settlement, even if adults are not. This may explain why a range of species have been observed to decline in abundance following large-scale losses of live coral. Understanding the habitat requirements of fishes throughout their life will enable more precise predictions to be made about the long term consequences of declining coral cover for reef fish assemblages.

Finally, more attention needs to be given to the potential for acclimation and adaptation of reef fishes to a changing climate. Ultimately, it is the potential for species to adapt to a changing climate that will set the boundaries for future population characteristics and geographical distributions.

References

1 Access Economics (2007) *Measuring the economic and financial value of the Great Barrier Reef Marine Park 2005/06*. Report by Access Economics Pty Limited for Great Barrier Reef Marine Park Authority. Great Barrier Reef Marine Park Authority.

2 Adams S, Mapstone BD, Russ GR and Davies CR (2000) Geographic variation in the sex ratio, sex specific size, and age structure of *Plectropomus leopardus* (Serranidae) between reefs open and closed to fishing on the Great Barrier Reef. *Canadian Journal of Fisheries and Aquatic Sciences* 57,1448–1458.

3 Almany GR (2004) Does increased habitat complexity reduce predation and competition in coral reef fish assemblages. *Oikos* 106, 275-284.

4 Armsworth PR (2000) Modelling the swimming response of late stage larval reef fish to different stimuli. *Marine Ecology Progress Series* 195, 231–247.

5 Barry JP, Baxter CH, Sagarin RD and Gilman SE (1995) Climate-related, long-term faunal changes in a Californian rocky intertidal community. *Science* 267, 672–675.

6 Bates ML, England MH and Sijp WP (2005) On the multi-century Southern Hemisphere response to changes in atmospheric CO_2 concentration in a Global Climate Model. *Meteorology and Atmospheric Physics* 89, 17–36.

7 Bay LK, Crozier RH and Caley MJ (2006) The relationship between population and genetic structure and pelagic larval duration in coral reef fishes on the Great Barrier Reef. *Marine Biology* 149, 1247–1256.

8 Begg GA, Mapstone BD, Williams AJ, Adams S, Davies CR and Lou DC (2005) Multivariate life-history indices of exploited coral reef fish populations used to measure the performance of no-take zones in a marine protected area. *Canadian Journal of Fisheries and Aquatic Sciences* 62, 679–692.

9 Bellwood DR, Hughes TP, Folke C and Nystrom C (2004) Confronting the coral reef crisis. *Nature* 429, 827–833.

10 Bellwood DR, Hoey AS, Ackerman JL and Depczyinski M (2006) Coral bleaching, reef fish community phase shifts and the resilience of coral reefs. *Global Change Biology* 12, 1587–1594.

11 Benoît HP, Pepin P and Brown JA (2000) Patterns of metamorphic age and length in marine fishes, from individuals to taxa. *Canadian Journal of Fisheries and Aquatic Sciences* 57, 856–869.

12 Bergenius MAJ, Meekan MG, Robertson DR and McCormick MI (2002) Larval growth predicts the recruitment success of a coral reef fish. *Oecologia* 131, 152–525.

13 Bergenius MAJ, McCormick MI, Meekan MG and Robertson DR (2005) Environmental influences on larval duration, growth and magnitude of settlement of a coral reef fish. *Marine Biology* 147, 291–300.

14 Berkelmans R, De'ath G, Kininmonth S, William J and Skirving W (2004) A comparison of the 1998 and 2002 coral bleaching events on the Great Barrier Reef: spatial correlation, patterns and predictions. *Coral Reefs* 23, 74–83.

15 Berumen ML and Pratchett MS (2006) Recovery without resilience: Persistent disturbance and long-term shifts in the structure of fish and coral communities at Tiahura Reef, Moorea. *Coral Reefs* 25, 647–653.

16 Beukers JS and Jones GP (1997) Habitat complexity modifies the impact of piscivores on a coral reef fish population. *Oecologica* 114, 50–59.

17 Beverton RJH (1992) Patterns of reproductive strategy parameters in some marine teleost fishes. *Journal of Fish Biology* 41, 137–160.

18 Blaber SJM and Blaber TG (1980) Factors affecting the distribution of juvenile estuarine and inshore fish. *Journal Fish Biology* 17, 143–162.

19 Boersma PD and Parrish JK (1999) Limiting abuse: Marine protected areas, a limited solution. *Ecological Economics* 31, 287–304.

20 Booth DJ and Beretta GA (2002) Changes in a fish assemblage after a coral bleaching event. *Marine Ecology Progress Series* 245, 205–212.

21 Booth DJ and Wellington G (1998) Settlement preferences in coral reef fishes: effects on patterns of adult and juvenile distributions, individual fitness and population structure. *Australian Journal of Ecology* 23, 274–279.

22 Booth DJ, Figueira WF, Gregson MA, Brown L and Beretta G (2007) Occurrence of tropical fishes in temperate southeastern Australia: Role of the East Australian Current. *Esturarine, Coastal and Shelf Science* 72, 102–114.

23 Bradshaw WE and Holzapfel CM (2006) Evolutionary response to rapid climate change. *Science* 312, 1477–1478.

24 Brown DJA and Sadler K (1989) Fish survival in acid waters. In: R Morris, EW Taylor, DJA Brown and JA Brown (eds) *Acid Toxicity and Aquatic Animals*. Cambridge University Press, Cambridge, pp. 31–44.

25 Bryden HL, Longworth HR and Cunningham SA (2005) Slowing of the Atlantic meridional overturning at 25 degrees N. *Nature* 438, 655–657.

26 Burgess SC, Kingsford MJ and Black MP (2007) Influence of tidal eddies and wind on the distribution of pre-settlement fishes around One Tree Island, Great Barrier Reef. *Marine Ecology Progress Series* 341, 233–242.

27 Cai W, Shi G, Cowan T, Bi T and Ribbe J (2005) The response of the Southern Annular Mode, the East Australian Current, and the southern mid-latitude ocean circulation to global warming. *Geophysical Research Letters* 32: L23706, doi: 10.1029/2005GL024701.

28 Caley MJ, Carr MH, Hixon MA, Hughes TP, Jones GP and Menge BA (1996) Recruitment and local dynamics of open marine populations. *Annual Review of Ecology and Systematics* 27, 477–500.

29 Cappo M, Speare P and De'ath G (2004) Comparison of baited remote underwater video stations (BRUVS) and prawn (shrimp) trawls for assessments of fish biodiversity in inter-reefal areas of the Great Barrier Reef Marine Park. *Journal of Experimental Marine Biology and Ecology* 302, 123–152.

30 Chavez FP, Ryan J, Lluch-Cota SE and Niquen C (2003) From anchovies to sardines and back: Multidecadal change in the Pacific Ocean. *Science* 299, 217–221.

31 Cheal AJ, Delean S, Sweatman H and Thompson AA (2007) Spatial synchrony in coral reef fish populations and the influence of climate. *Ecology* 88, 158–169.

32 Choat JH and Bellwood DR (1991) Reef fishes: Their history and evolution. In: PF Sale (ed) *The Ecology of Fishes on Coral Reefs*. Academic Press, San Diego, pp. 39–69.

33 Choat JH and Robertson DR (2002) Age-Based Studies. In: PF Sale (ed) *Coral Reef Fishes. Dynamics and Diversity in a Complex Ecosystem*. Academic Press, San Diego, pp. 57–80.

34 Claiborne JB, Edwards SL and Morrison-Shetlar AI (2002) Acid-base regulation in fishes: cellular and molecular mechanisms. *Journal of Experimental Zoology* 293, 302–319.

35 Coleman N (1980) *Australian sea fishes south of 30°S*. Doubleday, Sydney.

36 Colin PL (1992) Reproduction of the Nassau grouper, *Epinephelus striatus* (Pisces: Serranidae) and it's relationship to environmental conditions. *Environmental Biology of Fishes* 34, 357–377.

37 Conover DO (1984) Adaptive significance of temperature-dependent sex determination in a fish. *American Naturalist* 123, 297–313.

38 Cowen R (2002) Larval dispersal and retention and consequences for population connectivity. In: PF Sale (ed) *Coral Reef Fishes. Dynamics and Diversity in a Complex Ecosystem.* Academic Press, San Diego, pp. 149–170.

39 Cowen RK, Paris CB and Srinivasan A (2006) Scaling of connectivity in marine populations. *Science* 311, 522–527.

40 Danilowicz BS (1995) The role of temperature in spawning of the damselfish *Dascyllus albisella*. *Bulletin of Marine Science* 57, 624–636.

41 DEH (Department of the Environment and Heritage) (2004) *Assessment of the Queensland east coast Spanish mackerel fishery*. DEH, Canberra.

42 DEH (Department of the Environment and Heritage) (2005) *Assessment of the Queensland coral reef finfish fishery.* DEH, Canberra.

43 Depczynski M and Bellwood DR (2005) Shortest recorded vertebrate lifespan found in a coral reef fish. *Current Biology* 15, 288–289.

44 Devlin RH and Nagahama Y (2002) Sex determination and sex differentiation in fish: an overview of genetic, physiological, and environmental influences. *Aquaculture* 208, 191–364.

45 Doherty P (1991) Spatial and temporal patterns in recruitment. In: PF Sale (ed) *The Ecology of Fishes on Coral Reefs*. Academic Press, San Diego, pp. 261–293.

46 Doherty P (2002) Variable replenishment and the dynamics of reef fish populations. In: PF Sale (ed) *Coral Reef Fishes. Dynamics and Diversity in a Complex Ecosystem.*, Academic Press, San Diego, pp. 327–355.

47 Doherty PJ and Williams DMcB (1988) The replenishment of coral reef fish populations. *Oceanography and Marine Biology Annual Review* 26, 487–551.

48 Doherty PJ, Planes S and Mather P (1995) Gene flow and larval duration in seven species of fish from the Great Barrier Reef. *Ecology* 76, 2373–2391.

49 Edwards M and Richardson AJ (2004) Impact of climate change on marine pelagic phenology and trophic mismatch. *Nature* 430, 881–884.

50 Feely RA, Sabine CL, Lee K, Berelson W, Kleypas J, Fabry VJ and Millero FJ (2004) Impact of Anthropogenic CO_2 on the $CaCO_3$ system in the oceans. *Science* 305, 362–366.

51 Furnas M, Mitchell AW and Skuza M (1995) *Nitrogen and phosphorus budgets for the Central Great Barrier Reef shelf*. GBRMPA Research Publication no. 36, Great Barrier Reef Marine Park Authority, Townsville.

52 Gagan MK, Sandstrom MW and Chivas AR (1987) Restricted terrestrial carbon input to the continental shelf during Cyclone Winifred: Implications for terrestrial runoff to the Great Barrier Reef Province. *Coral Reefs* 6, 113–119.

53 Gardiner NM and Jones GP (2005) Habitat specialisation and overlap in a guild of coral reef cardinal fishes (Apogonidae). *Marine Ecology Progress Series* 305, 163–175.

54 Garpe KC, Yahya SAS, Lindahl U and Öhman MC (2006) Long-term effects of the 1998 coral bleaching event on reef fish assemblages. *Marine Ecology Progress Series* 315, 237–247.

55 Genner MJ, Sims DW, Wearmouth VJ, Southhall EJ, Southward AJ, Henderson PA and Hawkins SJ (2004) Regional climatic warming drives long-term community changes of British marine fish. *Proceedings of the Royal Society of London B* 271, 655–661.

56 Graham NAJ, Wilson SK, Jennings S, Polunin NVC, Bijoux JP and Robinson J (2006) Dynamic fragility of oceanic coral reef ecosystems. *Proceedings of the National Academy of Science* 103, 8425–8429.

57 GBRMPA (Great Barrier Reef Marine Park Authority) (2005) *Measuring the economic and financial value of the Great Barrier Reef Marine Park,* report prepared by Access Economics Pty Ltd, GBRMPA Research Publication no. 84, Great Barrier Reef Marine Park Authority, Townsville.

58 Green BS and Fisher R (2004) Temperature influences swimming speed, growth and larval duration in coral reef fish larvae. *Journal of Experimental Marine Biology and Ecology* 299, 115–132.

59 Gust N (2004) Variation in the population biology of protogynous coral reef fishes over tens of kilometers. *Canadian Journal of Fisheries and Aquatic Sciences* 61, 205–218.

60 Gust N, Choat JH and McCormick MI (2001) Spatial variability in reef fish distribution, abundance, size and biomass: A multi-scale analysis. *Marine Ecology Progress Series* 214, 237–251.

61 Gust N, Choat JH and Ackerman JL (2002) Demographic plasticity in tropical reef fishes. *Marine Biology* 140, 1039–1051.

62 Halford A, Cheal AJ, Ryan D and Williams DMcB (2004) Resilience to large-scale disturbance in coral and fish assemblages on the Great Barrier Reef, Australia. *Ecology* 85, 1892–1905.

63 Harley CDG, Hughes AR, Hultgren KM, Miner BG, Sorte CJB, Thornber CS, Rodriguez LF, Tomanek LW and Susan L (2006) The impacts of climate change in coastal marine systems. *Ecology Letters* 9, 228–241.

64 Hawkins AJS (1996) Temperature adaptation and genetic polymorphism in aquatic animals. In: IA Johnston and AF Bennett (eds) *Animals and Temperature: Phenotypic and Evolutionary Adaptation.* Cambridge University Press, Cambridge, pp. 103–125.

65 Hays GC, Richardson AJ and Robinson C (2005) Climate change and marine plankton. *Trends in Ecology and Evolution* 20, 337–344.

66 Hernaman V and Munday P (2005) Life-history characteristics of coral reef gobies. I. Growth and life-span. *Marine Ecology Progress Series* 290, 207–221.

67 Hilder ML and Pankhurst NW (2003) Evidence that temperature changes cues reproductive development in the spiny damselfish, *Acanthochromis polyacanthus. Environmental Biology of Fishes* 66, 187–196.

68 Hoegh-Guldberg O (1999) Climate change, coral bleaching and the future of the worlds coral reefs. *Marine and Freshwater Research* 50, 839–866.

69 Hoegh-Guldberg O (2005) Climate Change and Marine Ecosystems. In: TE Lovejoy and L Hannah (eds) *Climate Change and Biodiversity.* Yale University Press, New Haven and London, pp. 256–273.

70 Holbrook SJ, Russell SJ and Stephens JS (1997) Changes in an assemblage of temperate reef fishes associated with a climate shift. *Ecological Applications* 7, 1299–1310.

71 Holbrook SJ, Forrester GE and Schmitt RJ (2000) Spatial patterns in abundance of a damselfish reflect availability of suitable habitat. *Oecologia* 122, 109–120.

72 Hollowed AB and Wooster WS (2001) Pacific basin climate variability and patterns of Northeast pacific marine fish production. *Progress in Oceanography* 49, 257–282.

73 Houghton J (2004) *Global Warming: The Complete Briefing*, 3rd edition, Cambridge University Press, Cambridge.

74 Hughes L (2000) Biological consequences of global warming: is the signal already apparent? *Trends in Ecology and Evolution* 15, 56–61.

75 Hughes TP, Baird AH, Bellwood DR, Card M, Connolly SR, Folke C, Grosberg R, Hoegh-Guldberg O, Jackson JBC, Kleypas J, Lough JM, Marshall P, Nyström M, Palumbi SR, Pandolfi JM, Rosen B and Roughgarden J (2003) Climate change, human impacts, and the resilience of coral reefs. *Science* 301, 929–933.

76 Hunt von Herbing I (2002) Effects of temperature on larval fish swimming performance: the importance of physics to physiology. *Journal of Fish Biology* 61, 865–876.

77 Hyland SJ (2002) *An investigation of the impacts of ponded pastures on barramundi and other finfish populations in tropical coastal wetlands, final report*. Department of Primary Industries, Brisbane.

78 IPCC (Intergovernmental Panel on climate Change) (2001) Climate Change 2001. The Scientific Basis. In: JT Houghton, Y Ding, DJ Griggs, N Noguer, PJ van der Linden, X Dai, K Maskell, and CA Johnson (eds) *Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge United Kingdom and New York, NY, USA.

79 Ishimatsu A, Kikkawa T, Hayashi M, Lee K and Kita J (2004) Effects of CO_2 on marine fish: Larvae and adults. *Journal of Oceanography* 60, 731–741.

80 Jackson DA and Harvey HH (1995) Gradual reduction and extinction of fish populations in acid lakes. *Water, Air and Soil Pollution* 85, 389–394.

81 James MK, Armsworth PR, Mason LB and Bode L (2002) The structure of reef fish metapopulations: modelling larval dispersal and retention patterns. *Proceedings of the Royal Society of London B* 269, 2079–2086.

82 Jobling M (1997) Temperature and growth: Modulation of growth rate via temperature change. In: CM Wood and DG McDonald (eds) *Global Warming: Implications for Freshwater and Marine Fish*. Cambridge University Press, Cambridge, pp. 225–253.

83 Jones (1991) Post-recruitment processes in the ecology of coral reef fish populations: A multifactorial perspective. In: PF Sale (ed) *The Ecology of Fishes on Coral Reefs*. Academic Press, San Diego, pp. 183–230.

84 Jones GP and McCormick MI (2002) Numerical and energetic processes in the ecology of coral reef fishes. In: PF Sale (ed) *Coral Reef Fishes: Dynamics and Diversity in a Complex Ecosystem*. Academic Press, San Diego, pp. 221–238.

85 Jones GP, McCormick MI, Srinivasan M and Eagle JV (2004) Coral decline threatens fish biodiversity in marine reserves. *Proceedings of the National Academy of Science* 101, 8251–8253.

86 Jump AS and Peńuelas J (2005) Running to stand still: adaptation and the response of plants to rapid climate change. *Ecological Letters* 8, 1010–1020.

87 Kailola PJ, Williams MJ, Stewart PC, Reichelt RE, McNee A and Grieve C (1993) *Australian fisheries resources*. Bureau of Resource Sciences and Fisheries Research and Development Corporation, Canberra.

88 Kleypas JA, Feely RA, Fabry VJ, Langdon C, Sabine CL and Robbins LL (2006) *Impacts of Ocean Acidification on Coral Reefs and Other Marine Calcifiers: A Guide for Future Research*, report of a workshop held 18–20 April 2005, sponsored by the National Science Foundation, National Oceanographic and Atmospheric Administration and the US Geological Survey, St. Petersburg, Florida.

89 Kokita T and Nakazono A (2001) Rapid response of an obligately corallivorous filefish *Oxymonacanthus longirostris* (Monacanthidae) to a mass coral bleaching event. *Coral Reefs* 20, 155–158.

90 Kritzer JP (2002) Variation in the population biology of stripey bass *Lutjanus carponotatus* within and between two island groups on the Great Barrier Reef. *Marine Ecology Progress Series* 243, 191–207.

91 Kroon FJ (2005) Behavioural avoidance of acidified water by juveniles of four commercial fish and prawn species with migratory life stages. *Marine Ecology Progress Series* 285, 193–204.

92 Kuiter RH (1996) *Guide to Sea Fishes of Australia*. New Holland, Frenchs Forest.

93 Landsea CW, Harper BA, Hoarau K and Knaff JA (2006) Can we detect trends in extreme tropical cyclones? *Science* 131, 452–454.

94 Latif M, Boening C, Willebrand J, Biastoch A, Dengg J, Keenlyside N, Schweckendiek U and Madec G (2006) Is the thermohaline circulation changing? *Journal of Climate* 19, 4631–4637.

95 Lehodey P, Bertignac M, Hampton J, Lewis A and Picaut J (1997) El Niño Southern Oscillation and tuna in the western Pacific. *Nature* 389, 715–718.

96 Lehodey P, Fei C and Hampton J (2003) Modelling climate-related variability of tuna populations from a coupled ocean-biogeochemical-populations dynamics model. *Fisheries Oceanography* 12, 483-494.

97 Leis JM (1991) The pelagic stage of reef fishes: The larval biology of coral reef fishes. In: PF Sale (ed) *The Ecology of Fishes on Coral Reefs*. Academic Press, San Diego, pp. 183–230.

98 Leis JM and McCormick MI (2002) The biology, behaviour and ecology of the pelagic, larval stage of coral reef fishes. In: PF Sale (ed) *Coral Reef Fishes. Dynamics and Diversity in a Complex Ecosystem*. Academic Press, San Diego, pp. 171–199.

99 Lewis AR (1997a) Recruitment and post-recruitment immigration affect the local population size of coral reef fishes. *Coral Reefs* 16, 139–149.

100 Lewis AR (1997b) Effects of experimental coral disturbance on the structure of fish communities on large patch reefs. *Marine Ecology Progress Series* 161, 37–50.

101 Loreau M, Naeem S, Inchausti P, Bengtsson J, Grime JP, Hector A, Hooper DU, Huston MA, Raffaelli D, Schmid B, Tilman D and Wardle DA (2001) Biodiversity and ecosystem functioning: Current knowledge and future challenges. *Science* 294, 804–808.

102 Lu H-J, Lee K-T, Lin H-L and Liao CH (2001) Spatio-temporal distribution of yellowfin tuna *Thunnus albacares* and bigeye tuna *Thunnua obesus* in the tropical Pacific Ocean in relation to large-scale temperature fluctuation during ENSO episodes. *Fisheries Science* 67, 1046–1052.

103 McCook LJ (1999) Macroalgae, nutrients and phase shifts on coral reefs: scientific issues and management consequences for the Great Barrier Reef. *Coral Reefs* 18, 357–367.

104 McCook LJ, Jompa J and Diaz-Pulido G (2001) Competition between corals and algae on coral reefs: a review of evidence and mechanisms. *Coral Reefs* 19, 400–417.

105 McCormick MI and Molony BW (1995) Influence of water temperature during the larval stage on size, age and body condition of a tropical reef fish at settlement. *Marine Ecology Progress Series* 118, 59–68.

106 McLean RF, Tsyban A, Burkett V, Codignotto JO, Forbes DL, Mimura N, Beamish RJ and Ittekkot V (2001) Coastal zones and marine ecosystems In: JJ McCarthy, OF Canziani, NA Leary, DJ Dokken and KS White (eds) *Climate change 2001: Impacts, Adaptation, and Vulnerability. Contribution of working group II to the third assessment report of the Intergovernmental Panel on Climate Change*, Cambridge University Press, Cambridge.

107 Marshall PA and Baird AH (2000) Bleaching of corals on the Great Barrier Reef: differential susceptibilities among taxa. *Coral Reefs* 19, 155–163.

108 Meekan MG, Wellington GM and Axe L (1999) El Niño- Southern Oscillation events produce checks in the otoliths of coral reef fishes in the Galapagos Archipelago. *Bulletin of Marine Science* 64, 383–390.

109 Meekan MG, Ackerman JL and Wellington GM (2001) Demography and age structures of coral reef damselfishes in the tropical eastern Pacific Ocean. *Marine Ecology Progress Series* 212, 223–232.

110 Meekan MG, Carleton JH, McKinnon AD, Flynn K and Furnas M (2003) What determines the growth of tropical reef fish larvae in the plankton: food or temperature? *Marine Ecology Progress Series* 256, 193–204.

111 Messmer V, van Herwerden L, Munday PL and Jones GP (2005) Phytogeography of colour polymorphism in the coral reef fish *Pseudochromis fuscus* from Papua New Guinea and the Great Barrier Reef. *Coral Reefs* 24, 392–402.

112 Mora C and Ospína AF (2001) Tolerance to high temperatures and potential impact of sea warming on reef fishes of Gorgona Island (tropical eastern Pacific). *Marine Biology* 139, 765–769.

113 Munday PL (2004) Habitat loss, resource specialization, and extinction on coral reefs. *Global Change Biology* 10, 1642–1647.

114 Munday PL and Holbrook SJ (2006) Changing coral communities: what are the consequences for reef fishes? *Proceedings of 10th International Coral Reef Symposium*, Okinawa 214–215.

115 Munday PL and Jones GP (1998) The ecological implications of small body size among coral-reef fishes. *Oceanography and Marine Biology: Annual Review* 36, 371–411.

116 Munday PL, Jones GP and Caley MJ (1997) Habitat specialisation and the distribution and abundance of coral-dwelling gobies. *Marine Ecology Progress Series* 152, 227–239.

117 Murawski SA (1993) Climate change and marine fish distributions: Forecasting from historical analogy. *Transactions of American Fisheries Society* 122, 647–658.

118 Myers RF (1999) *Micronesian Reef Fishes*. 3rd edition. Coral Graphics, Guam.

119 Nagelkerken IS, Kleijnen T, Klop R, Van den Brand E, De la Moriniere C, and Van der Velde G (2001) Dependence of Caribbean reef fishes on mangroves and seagrass beds as nursery habitats: A comparison of fish faunas between bays with and without mangroves/seagrass beds. *Marine Ecology Progress Series* 214, 225–235.

120 Newman SJ, Williams DMcB and Russ GR (1997) Patterns of zonation of assemblages of the Lutjanidae, Lethrinidae and Serrenidae (Epinephelinae) within and among mid-shelf and outer-shelf reefs in the central Great Barrier Reef. *Marine and Freshwater Research* 48, 119–128.

121 O'Brien CM, Fox CJ, Planque B and Casey J (2000) Fisheries: Climate variability and North Sea cod. *Nature* 404, 142.

122 Öhman MC, Munday PL, Jones GP and Caley MJ (1998) Settlement strategies and distribution patterns of coral-reef fishes. *Journal of Experimental Marine Biology and Ecology* 225, 219–238.

123 Ottersen G, Hjermann DØ and Stenseth NC (2006) Changes in spawning stock structure strengthen the link between climate and recruitment in a heavily fished cod (*Gadus morhua*) stock. *Fisheries Oceanography* 15, 230–243.

124 Parker RO Jr and Dixon RL (1998) Changes in a North Carolina reef fish community after 15 years of intense fishing – global warming implications. *Transactions of the American Fisheries Society* 127, 908–920.

125 Parmesan C and Yohe G (2003) A globally coherent fingerprint of climate change impacts across natural systems. *Nature* 421, 37–42.

126 Pears RJ, Choat JH, Mapstone BD and Begg GA (2006) Demography of a large grouper, *Epinephelus fuscoguttas*, from Australia's Great Barrier Reef: Implications for fishery management. *Marine Ecology Progress Series* 307, 259–272.

127 Perry ALL, Ellis PJ and Reynolds JD (2005) Climate change and distribution shifts in marine fishes. *Science* 308, 1912–1915.

128 Pittock B (2003) *Climate change: An Australian guide to the science and potential impacts*. Australian Greenhouse Office, Canberra.

129 Polovina JJ (1996) Decadal variation in the trans-Pacific migration of northern bluefin tuna (*Thunnus thynnus*) coherent with climate-induced change in prey abundance. *Fish Oceanography* 5, 114–119.

130 Polovina JJ (2005) Climate variation, regime shifts, and implications for sustainable fisheries. *Bulletin of Marine Science* 76, 233–244.

131 Pörtner HO, Langenbuch M and Reipschlager A (2004) Biological impact of elevated ocean CO_2 concentrations: Lessons from animal physiology and earth history. *Journal of Oceanography* 60, 705–718.

132 Pratchett MS (2005) Dietary overlap among coral-feeding butterflyfishes (Chaetodontidae) at Lizard Island, northern Great Barrier Reef. *Marine Biology* 148, 373–382.

133 Pratchett MS, Wilson SK, Berumen ML and McCormick MI (2004) Sublethal effects of coral bleaching on an obligate coral feeding butterflyfish. *Coral Reefs* 23, 352–356.

134 Pratchett MS, Wilson SK and Baird AH (2006) Declines in the abundance of Chaetodon butterflyfishes (Chaetodontidae) following extensive coral depletion. *Journal of Fish Biology* 69, 1269–1280.

135 Pratchett MS, Wilson SK, Graham NAJ, Munday PL, Jones GP and Polunin NVC (In press) Coral bleaching and consequences for mobile reef organisms: past, present and uncertain future. In: M Van Oppen and J Lough (eds) *Coral Bleaching: Patterns, Processes, Causes and Consequences.* Springer, Hieldelberg.

136 Randall JE (2005) *Reef and Shore Fishes of the South Pacific.* University of Hawaii Press, Honolulu.

137 Randall JE, Allen GR and Steene RC (1997) *Fishes of the Great Barrier Reef and Coral Sea*. University of Hawaii Press, Honolulu.

138 Reid PC, de Fatima Borges M and Svendsen E (2001) A regime shift in the North Sea circa 1988 linked to changes in the North Sea horse mackerel fishery. *Fisheries Research* 50, 163–171.

139 Robertson AI and Duke NC (1987) Mangroves as nursery sites: Comparisons of the abundance and species composition of fish and crustaceans in mangroves and other nearshore habitats in tropical Australia. *Marine Biology* 96, 193–205.

140 Robertson DR (1991) The role of adult biology in the timing of spawning of tropical reef fishes. In: PF Sale (ed) *The ecology of fishes on coral reefs.* Academic Press, san Diego, pp. 356–386.

141 Robertson DR, Ackerman JL, Choat JH, Posada JM and Pitt J (2005) Ocean surgeon fish *Acanthurus bahianus*. I. The geography of demography. *Marine Ecology Progress Series* 295, 229–224.

142 Roessig JM, Woodley CM, Cech JJ and Hansen LJ (2004) Effects of global climate change on marine and estuarine fishes and fisheries. *Reviews in Fish Biology and Fisheries* 14, 251–275.

143 Rombough PJ (1997) The effects of temperature on embryonic and larval development. In: CM Wood and DG McDonald (eds) *Global Warming: Implications for Freshwater and Marine Fish.* Cambridge University Press, Cambridge, pp. 177–223.

144 Root TL, Hall KR, Schnelders SH, Rosenzweig C and Pounds A (2003) Fingerprints of global warming on wild animals and plants. *Nature* 421, 57–60.

145 Royal Society (2005) *Ocean acidification due to increasing atmospheric carbon dioxide.* The Royal Society, London.

146 Russ G (1984a) Distribution and abundance of herbivorous grazing fishes in the central Great Barrier Reef. I. Levels of variability across the entire continental shelf. *Marine Ecology Progress Series* 20, 23–34.

147 Russ G (1984b) Distribution and abundance of herbivorous grazing fishes in the central Great Barrier Reef. II. Patterns of zonation of mid-shelf and outershelf reefs. *Marine Ecology Progress Series* 20, 35–44.

148 Russell BC (1983) *Annotated checklist of the coral reef fishes in the Capricorn-Bunker Group, Great Barrier Reef, Australia*, Great Barrier Reef Marine Park Authority, Townsville.

149 Russell DJ and Garrett RN (1983) Use by juvenile barramundi, *Lates calcarifer* (Bloch), and other fishes of temporary supralittoral habitats in a tropical estuary in northern Australia. *Australian Journal Marine Freshwater Research* 34, 805–811.

150 Ruttenberg BI, Haupt AJ, Chiriboga AI and Warner RR (2005) Patterns, causes and consequences of regional variation in the ecology and life history of a reef fish. *Oecologia* 145, 394–403.

151 Sadovy Y (1996) Reproduction of reef fisheries species. In: NVC Polunin and CM Roberts (eds) *Reef Fisheries.* Chapman and Hall, London, pp. 15–59.

152 Sale PF (1991) Reef fish communities: Open nonequilibrial systems. In: PF Sale (ed) *The Ecology of Fishes on Coral Reefs.* Academic Press, San Diego, pp. 261–293.

153 Samoilys MA (1997) Periodicity of spawning aggregations of coral trout *Plectropomus leopardus* (Pisces: Serranidae) on the northern Great Barrier Reef. *Marine Ecology Progress Series* 160, 149–159.

154 Sano M, Shimizu M and Nose Y (1987) Long-term effects of destruction of hermatypic corals by *Acanthaster planci* infestation on reef fish communities at Iriomote Island, Japan. *Marine Ecology Progress Series* 37, 191–199.

155 Searcy SP and Sponaugle S (2000) Variable larval growth in a coral reef fish. *Marine Ecology Progress Series* 206, 213–226.

156 Sheaves MJ (1995) Large lutjanid and serranid fishes in tropical estuaries: Are they adults of juveniles? *Marine Ecology Progress Series* 129, 31–40.

157 Sheaves MJ (2005) Nature and consequences of biological connectivity in mangrove systems. *Marine Ecology Progress Series* 302, 293-305.

158 Sheaves MJ (2006) Is the timing of spawning in sparid fishes a response to sea temperature regimes? *Coral Reefs* 25, 655–669.

159 Sheaves M and Molony B (2000) Short-circuit in the mangrove food chain. *Marine Ecology Progress Series* 199, 97–109.

160 Sheaves MJ, Collins W, Houston P, Dale A, Revill R, Johnston WA and Abrantes K (2006) *Contribution of floodplain wetland pools to the ecological functioning of the Fitzroy River estuary*. Cooperative Research Center for Coastal Zone, Estuarine and Waterway Management, Brisbane.

161 Shirayama Y and Thornton H (2005) Effects of increased atmospheric CO_2 on shallow water marine benthos. *Journal of Geophysical Research* 110: C09S08, doi:10.1029/2004JC002618.

162 Southward AJ, Langmead O, Hardman-Mountford J, Aiken J, Boalch GT, Dando PR, Genner MJ, Joint I, Kendall MA, Halliday NC, Harris RP, Leaper R, Mieszkowska N, Pingree RD, Richardson AJ, Sims DW, Smith T, Walne AW and Hawkins SJ (2004) Long-term trends oceanographic and ecological research in the western English Channel. *Advances in Marine Biology* 47, 1–105.

163 Spalding MD and Jarvis GE (2002) The impact of the 1998 coral mortality on reef fish communities in the Seychelles. *Marine Pollution Bulletin* 44, 309–321.

164 Srinivasan M and Jones GP (2006) Extended breeding and recruitment periods of fishes on a low latitude coral reef. *Coral Reefs* 25, 673–682.

165 Stachowicz JJ, Whitlatch RB and Osman RW (2002) Linking climate change and biological invasions: Ocean warming facilitates nonindigenous species invasions. *Proceedings of National Academy of Science* 99, 15497–15500.

166 Steneck RS (1997) Crustose corallines, other algal functional groups, herbivores and sediments: Complex interactions among reef productivity gradients. *Proceedings of the 8th International Coral Reef Symposium* 1, 695-700.

167 Stocker TF and Schmittner A (1997) Influence of CO_2 emission rates on the stability of thermohaline circulation. *Nature* 388, 862–865.

168 Syms C and Jones GP (2000) Disturbance, habitat structure, and the dynamics of a coral-reef fish community. *Ecology* 81, 2714–2729.

169 Tilman D (1999) The ecological consequences of changes in biodiversity: A search for general principles. *Ecology* 80, 1455–1474.

170 Van Der Kraak G and Pankhurst NW (1997) Temperature effects on the reproductive performance of fish. In: CM Wood and DG McDonald (eds) *Global Warming: Implications for Freshwater and Marine Fish.* Cambridge University Press, Cambridge, pp. 159–176.

171 Visser ME and Both C (2005) Shifts in phenology due to global climate change: the need for a yardstick. *Proceedings of the Royal Society of London B* 272, 2561–2569.

172 Wallace AR (1869) *The Malay Archipelago*, 10th edition, PenPlus Ltd., London.

173 Walther GR, Convey PE, Menzel A, Parmesan C, Beebee TJC, Fromentin J-M, Hoegh-Guldberg O, and Bairlein F (2002) Ecological responses to recent climate change. *Nature* 416. 389–395.

174 Wassenberg TJ, Blaber SJM, Burridge CY, Brewer DT, Salini JP and Gribble N (1997) The effectiveness of fish and shrimp trawls for sampling fish communities in tropical Australia. *Fisheries Research* 30, 241–251.

175 Webster PJ, Holland GJ, Curry JA and Chang H-R (2005) Changes in tropical cyclone number and intensity in a warming environment. *Science* 309, 844–1846.

176 Wilkinson C (2002) Executive summary: Status of coral reefs of the world 2002. In: C Wilkinson (ed) *Status of Coral Reefs of the World 2002.* Australian Institute of Marine Science, Townsville, pp. 7–31.

177 Williams AJ, Davies CR, Mapstone BD and Russ GR (2003) Scales of spatial variation in demography of a large coral reef fish: An exception to the typical model? *Fisheries Bulletin* 101, 673–683.

178 Williams AJ, Mapstone BD and Davies CR (2007) Spatial patterns in cohort-specific mortality of red throat emperor, *Lethrinus miniatus,* on the Great Barrier Reef. *Fisheries Research* 84, 328–337.

179 Williams DMcB (1991) Patterns and processes in the distribution of coral reef fishes. In: PF Sale (ed) *The Ecology of Fishes on Coral Reefs.* Academic Press, San Diego, pp. 437–474.

180 Williams DMcB (1994) *Coral Sea Region billfish atlas: seasonal distribution and abundance of billfish species around the Coral Sea rim, Solomon Islands, Papua New Guinea, Vanuatu*, Australian Institute of Marine Science, Townsville.

181 Williams DMcB and Hatcher AI (1983) Structure of fish communities on outer slopes of inshore, mid-shelf and outer shelf reefs on the Great Barrier Reef. *Marine Ecology Progress Series* 10, 239–250.

182 Williams LE (2002) *Queensland's Fisheries Resources. Current Trends and Condition 1988-2000*. Department of Primary Industries, Brisbane.

183 Wilson DT and Meekan MG (2002) Growth-related advantages for survival to the point of replenishment in the coral reef fish *Stegastes partitus* (Pomacentridae). *Marine Ecology Progress Series* 231, 247–260.

184 Wilson SK, Graham NAJ, Pratchett MS, Jones GP and Polunin NVC (2006) Multiple disturbances and the global degradation of coral reefs: are reef fishes at risk or resilient? *Global Change Biology* 12, 2220–2234.

185 Wood CM and McDonald DG (1997) *Global Warming: Implications for Freshwater and Marine Fish.* Cambridge University Press, Cambridge.

186 Worm B and Myers RA (2004) Managing fisheries in a changing climate. No need to wait for more information: industrialised fishing is already wiping out stocks. *Nature* 429, 15.

187 Worm B, Sandow M, Oschlies A, Lotze HK and Myers RA (2005) Global patterns of predator diversity in the open oceans. *Science* 309, 1365-1369.

188 Zagarese and Williamson (2001) The implications of solar UV radiation exposure for fish and fisheries. *Fisheries* 2, 250–260.