

Marine Climate Change in Australia

Impacts and Adaptation Responses **2009 REPORT CARD**

Tropical Coastal Fish

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Summary: Climate change will affect populations and communities of marine fishes in many ways, ranging from indirect effects associated with habitat degradation and altered resource availability to direct effects of rapidly changing environmental conditions. In the short-term (up to 2030), the impact of climate change on Australia's tropical coastal and demersal fishes is largely tied to the fate of critical benthic habitats, especially for coral reef environments, which are highly vulnerable to elevated temperature and ocean acidification. There is good evidence and high consensus that climate-induced coral bleaching affects the community structure and abundance of reef-associated fishes, especially when it leads to the structural collapse of reef habitat. In the longer-term (after 2030), sea level rise and altered rainfall patterns will also significantly alter coastal wetlands that are important nursery areas for estuarine and nearshore species. In addition to the effects of habitat degradation, warmer ocean temperatures will cause distributional shifts in some tropical fishes, increasing the geographic ranges of some species and decreasing the ranges of others, including some commercially important species. Life history traits and population dynamics will be affected by warmer temperatures, with potential implications for fisheries yields. Altered oceanic circulation and ocean acidification could have very significant effects on populations and communities of coastal fishes. However, these impacts are still poorly understood and are likely to become most apparent in the longer term. There are many critical knowledge gaps in our understanding of the effect of climate change on tropical marine fish, including the impact of warmer temperatures on adult reproduction, and the development, survival and behaviour of larvae; the effect of ocean acidification on the development, survival and behaviour; and the degree to which fish will acclimate or adapt to the expected rapid climate change. Non-reefal environments and commercially important species are especially understudied in relation to climate change impacts. Key strategies in mitigating effects of climate change on coastal marine

fishes are to maintain and restore habitat quality, incorporate climate uncertainty into fisheries management plans, and limit impacts of other human activities in coastal regions.

Introduction

Australia has over 1.5 million km² of tropical coastal waters (territorial area within the continental shelf) extending from Queensland and the Great Barrier Reef on the east coast, across the Northern Territory and Arafura Sea region, to Western Australia and Ningaloo Reef on the west coast. These waters are inhabited by approximately 2000 species of marine fishes (Allen and Swainston 1988). The vast majority of species live on or around coral reefs (Randall et al. 1997, Choat and Russell 2009), with a smaller number of species inhabiting inter-reefal areas, inshore and estuarine water, or the pelagic zone above the continental shelf.

Although most coastal fishes are closely associated with reefs or other benthic substratum as adults, nearly all species have a lifecycle that includes a pelagic larval stage, which lasts for a period of weeks to months, depending on the species (Leis 1991). When sufficiently developed, the larvae settle to the benthos, usually in the same general habitat as juveniles and adults (Booth and Wellington 1998). A few species, such as some snappers and groupers, settle into shallow inshore and estuarine habitats and migrate to reefs or deeper inter-reefal areas as juveniles or subadults (Sheaves 2005).

Climate change will affect populations and communities of coastal and demersal fishes through a range of impacts on the larval, juvenile or adult phases (Munday et al. 2008a, 2009a). Changes to sea surface temperature (SST), ocean pH, and circulation patterns are expected to influence a suite of biological and ecological characteristics of marine fishes, including: physiological condition, life history traits, the timing of breeding, reproductive output, larval development, population connectivity and geographic distributions (Table 1). The effects of climate change on food supply and habitat quality are predicted to have further significant effects on fish populations and communities (Table 1). In the short-term, the greatest effects of climate change on coastal fishes is expected to be caused by degradation of shallow marine habitats, especially for coral reef environments (Munday et al. 2007, 2008a, Pratchett et al. 2008) which are particularly sensitive to increasing temperatures and declining ocean pH (Hoegh-Guldberg et al. 2007). In the longer-term sea level rise and altered rainfall patterns will also alter the distribution and quality of coastal wetlands that are important nursery areas for many estuarine and nearshore species.

Predicting the changes that will occur to tropical coastal fishes as a result of climate change is challenging because of complex interactions between the physical environment, physiological and behavioural responses of fishes at different life history stages, energy transfer between trophic levels, and the effect of habitat structure on ecological processes and interactions (Figure 1). Furthermore, relatively little research has been conducted on the effects that changes to the physical environment have on the ecology and biology of tropical marine fishes. Consequently, confidence in most predictions about the impact of climate change to Australia's coastal fishes is moderate-low, and unforeseen impacts are likely to occur.

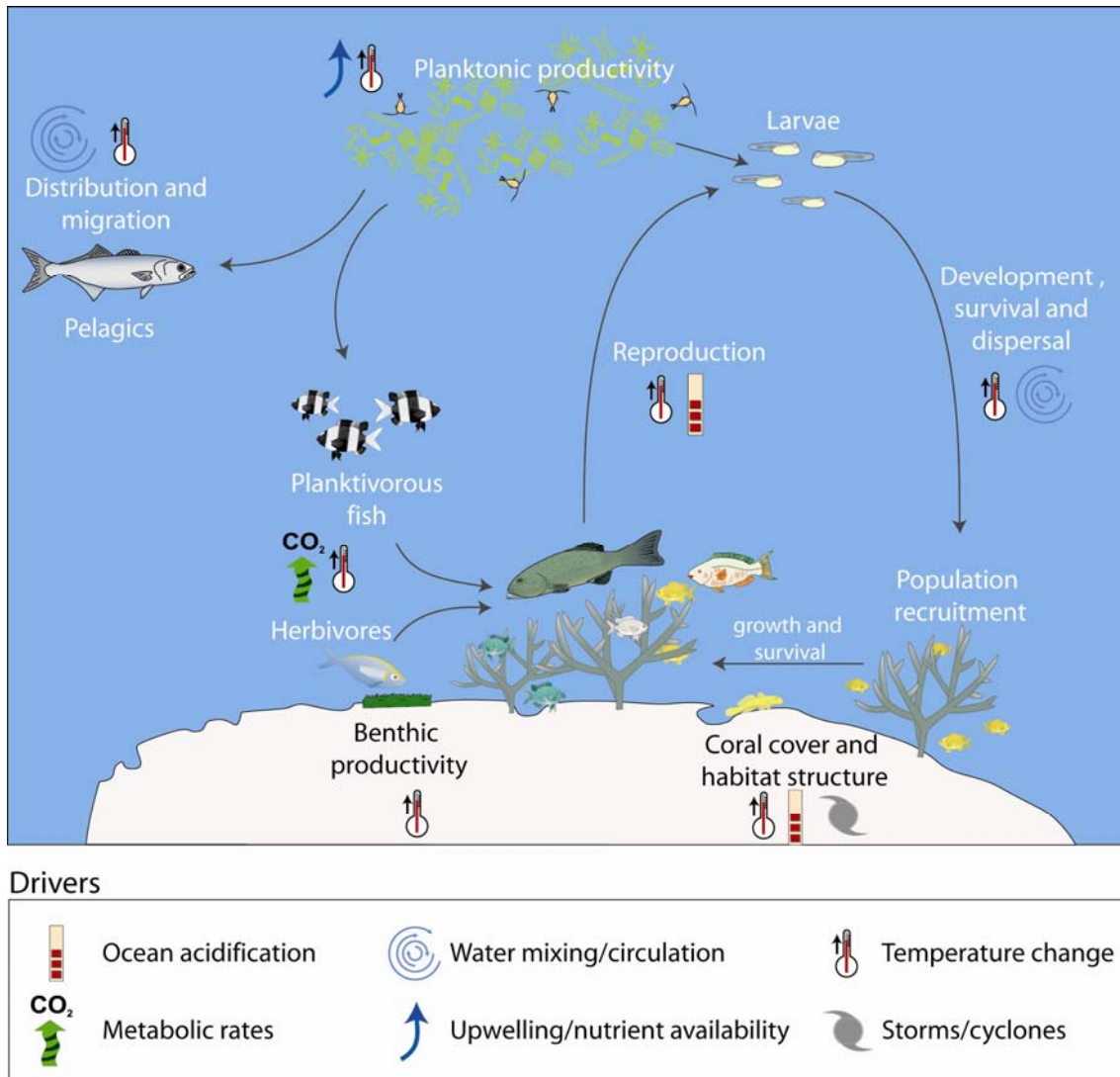


Figure 1. The impacts of climate change on populations and communities of tropical coastal fishes will depend on complex interactions between changes in the physical environment (e.g. changes in SST, currents and upwelling, storms, ocean pH), physiological and behavioural responses of fishes at different life history stages, energy transfer between trophic levels, and the effect of habitat structure on ecological processes and interactions. From Munday et al. 2007.

Observed Impacts

Coral reefs have been studied more intensively than other tropical marine environments. Recent episodes of coral bleaching caused by elevated sea temperatures have seriously degraded reefs around the world (Wilkinson 2004). Coral mortality from bleaching has caused significant declines in the diversity and abundances of reef fishes in some places

(Jones et al. 2004, Pratchett et al. 2008) especially in locations where the structural complexity of the reef habitat has been significantly reduced (Graham et al. 2006). The amount of suitable habitat for reef fishes is further reduced if the effects of coral bleaching interact with other disturbances that kill live coral, such as outbreaks of crown of thorns starfish, severe storms, or terrestrial pollution. The interacting effects of climate change and other stresses to reef habitats have the potential to substantially alter the structure of fish communities in tropical Australia (Wilson 2008a).

Loss of live coral cover has the greatest effect on those species of fish that rely on live coral for diet, habitat or settlement (Wilson et al. 2006, Pratchett et al. 2008). Declines in population abundance in these species can occur rapidly following coral loss, and are greatest for more specialised species, such as those that live or feed on just 1-2 species of coral (Munday 2004, Pratchett et al. 2006, Wilson et al. 2008b). Importantly, many reef fish that specialise on live coral are dependent on coral species that are susceptible to coral bleaching (e.g. Acroporidae and Pocilloporidae; Marshall and Baird 2000). If coral does not recover in the longer-term (after 5-10 years), impacts can be more substantial with up to 75% of fish species declining in abundance, including many species with no apparent reliance on live coral (Jones et al. 2004, Cheal et al. 2008). Skeletons of dead corals ultimately erode and collapse thereby reducing topographic and habitat complexity. This leads to further changes to the fish community, including reductions in species richness, taxonomic distinctness and abundance (Graham et al. 2006). Declines are often greatest for smaller-bodied species <20cm (Graham et al. 2008). However, smaller size classes of larger species also decline in some instances, suggesting that the contribution of these species to ecosystem function and fisheries could be undermined in the future (Graham et al. 2007).

Australia's coral reefs have suffered several significant episodes of coral bleaching since the mid 1990's. During the 1998 global mass bleaching event sea surface temperatures in the GBR reached the highest ever recorded. About 50% of reefs suffered bleaching, with more bleaching on inshore reefs compared with mid-shelf and offshore reefs. Inshore reefs also suffered the highest coral mortality rates. Overall, about 5% of reefs were severely damaged. Another severe bleaching event in 2002 also affected about 50% of reefs and also severely damaged about 5% of reefs, this time including mid-shelf and offshore reefs. A severe bleaching event in the southern GBR in 2006 caused 40% coral mortality in the Keppel Islands (Great Barrier Reef Marine Park Authority 2007), but little impact elsewhere.

The long-term monitoring program (LTMP) conducted by the Australian Institute of Marine Science (AIMS) (<http://www.aims.gov.au/reef-monitoring>) provides the best available data set to assess the broad-scale impacts of ecological disturbances to fishes on the Great Barrier Reef (GBR). Other disturbances, such as outbreaks of crown-of-thorns starfish and severe storms, have also impacted reef habitats since the mid 1990's, consequently it is difficult to isolate the potential effects of climate change from other disturbances in this data set. Nevertheless, it still provides an important indicator of the current condition of fish communities on the GBR and likely changes that will occur due to predicted increases in the intensity and frequency of coral bleaching (Hoegh-Guldberg 1999, Donner et al. 2005). Averaged across all 48 reefs surveyed by the LTMP, there has been little change in the mean abundance, species richness, and diversity of fish communities sampled between 1993-2007 (Delean and De'ath 2008). Similarly, there has been little change in the averaged abundances of major trophic groups of fishes including herbivores, planktivores, benthic feeders and predators across all reefs (Delean and De'ath 2008). There have, however, been large and important

changes in fish abundance and community structure at specific reefs where significant declines in coral cover have occurred (Halford et al. 2004, Cheal et al. 2008).

In the most comprehensive study to date, Cheal et al. (2008) found that fish diversity was not affected on 7 reefs that suffered over 75% coral loss from a variety of disturbances between 1995-2005. There were, however, major changes in fish community structure that involved increases in abundance of large herbivores and decreases in abundance of both coral-dependent fishes and species with no obvious dependence on coral. The proportion of species that increased or decreased in abundance varied among reefs, but 45 to 71% of fish species decreased in abundance on some reefs. The magnitude of change in species abundances increased linearly with the magnitude of coral decline. Bellwood et al. (2006) and Wilson et al. (2009) also reported significant changes in fish community structure on GBR reefs affected by major disturbances (including coral bleaching), with decreases in coral-dependent species and increases in small generalist species, epilithic algal feeders and rubble dwellers. Finally, Booth and Beretta (2002) observed significant declines in the recruitment of 3 species of damselfishes at One Tree Island immediately following the 1997-1998 bleaching event. Together these studies indicate that coral bleaching in conjunction with other major agents of disturbance has already had a significant effect on the abundances and community structure of fishes on some reefs on the Great Barrier Reef. They also suggest that significant changes to fish communities will become more widespread if mass coral bleaching events occur more frequently in the future (Table 2).

The structure of fish communities also changed substantially at Scott Reef in Western Australia following mass coral bleaching in 1998 (Halford and Caley 2009). Species richness declined in 4 fish families following the bleaching, but had recovered in 2 of them (surgeonfishes and parrotfishes) within 5 years. In the other 2 families (butterflyfishes and damselfishes), both species richness and total abundance declined and remained lower than pre-bleaching after 5 years, especially on the reef slope. Changes in fish community structure tended to lag behind changes in the benthic habitat by 12-18 months. Recovery of fish communities was observed as coral cover returned, but was still incomplete after 5 years.

Although a range of other impacts on tropical coastal fishes are predicted (Table 1), few have yet been detected. There are indications, however, that some of these impacts are already occurring. Geographic range shifts are a common signature of climate change responses, with many species expanding to higher latitudes in both terrestrial and aquatic ecosystems as global temperatures increase (Hickling et al. 2006, Parmesan 2006). Similar shifts by tropical marine fishes are predicted to occur in Australian waters (Munday et al. 2007). Recruits of tropical species are being recorded in increased abundance in sub-tropical and temperate locations and in some instances have persisted for several years (Booth et al. 2007). Persistence is largely determined by overwintering temperatures, which have been increasing over the past decade (Figueira and Booth 2009). This indicates that range shifts by tropical species towards higher latitudes is already underway.

Many tropical marine fishes have large latitudinal ranges that extend across temperature gradients of 3-4°C. Life history traits of some species covary in a predictable way with these latitudinal and temperature gradients (Choat and Robertson 2002, Robertson et al. 2005). Reef fish species tend to be shorter lived and reach smaller maximum sizes at higher temperatures (Munday et al. 2008a). Juveniles are also expected to reach their asymptotic size at a faster rate at higher temperatures. Recently, Meekan et al.

(unpublished data) found that early growth of the Western Gregory, *Stegastes obreptus*, had increased significantly in the sub-tropical Abrolhos Islands in association with a 1.6°C increase in average SST at this location over the past 25 years. This is the first evidence that life history traits of tropical marine fishes may be changing as predicted in local populations of tropical marine fishes.

Finally, small increases in SST are predicted to increase larval survival of marine species by reducing pelagic duration (O'Connor et al. 2007). Consistent with this prediction, Cheal et al. (2007) found that large population increases of damselfishes on the GBR often followed elevated SST associated with El Niño events.

Potential impacts by the 2030s and 2100s

Sea Surface Temperature

Increased SST is predicted to have a range of impacts on tropical fish populations and communities (Table 1). Fishes are ectotherms and temperature changes of a few degrees Celsius can influence their physiological condition, developmental rate, growth rate, reproductive performance and behaviour. Consequently, the projected 1-2°C increase in SST by 2030 and 2-3°C increase by 2100 are expected to have significant impacts on coastal marine fishes.

Increased temperature could have either a positive or negative effect on adult performance, depending on the current temperatures experienced by individuals relative to their thermal optimum for physiological activities (Munday et al. 2008a). At least some tropical coastal fishes appear to be closely adapted to the local thermal environment (Pankhurst and Porter 2003), with growth rates and reproductive capacity declining at higher temperatures, even when additional food is available to fuel higher metabolic rates at higher temperatures. For example, adults of the spiny damselfish, *Acanthochromis polyacanthus*, lost weight when reared at 3°C above the average summer temperatures experienced in the wild, regardless of the amount of food they consumed (Munday et al. 2008b). Reproduction of *A. polyacanthus* is even more sensitive to increased temperature, with the numbers of pairs laying eggs, clutch size, and egg size all being reduced at 1.5°C above the average summer temperatures and further declines evident at 3°C above summer temperatures (Donelson et al. 2010). Increased temperature (2 °C) has also been shown to increase embryo mortality of the common tropical marine fish *Pomacentrus amboinensis* (Gagliano et al. 2007). Furthermore, there is good evidence that some species from predominantly temperate water fish families (eg *Pagrus auratus*: Sparidae) are already at their thermal limit for reproduction in tropical waters (Sheaves 2006). Together these results suggest that reproductive performance of some species will be affected as early as 2030 and many species could be impacted by 2100 (Table 2).

The breeding season is probably cued by temperature in many tropical species (Hilder and Pankhurst 2003, Pankhurst and Porter 2003). Consequently, the effects of increasing temperature on reproductive performance could potentially be ameliorated to some extent by shifts in the seasonal timing of breeding (Munday et al. 2008a), however this could lead to a mismatch in the optimal time for reproduction compared with the optimal time for larval survival (Edwards and Richardson 2004). The greatest problems are expected for fish that use photoperiod to cue reproduction, because these species may not shift the breeding season as SST increases.

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Early developmental stages of reef fishes are particularly sensitive to temperature changes. Evidence suggests that small temperature increases will accelerate larval development, increase larval growth rate, and reduce pelagic larval duration (PLD; McCormick and Molony 1995, Wilson and Meekan 2002, Meekan et al. 2003, Green and Fisher 2004, Sponaugle et al 2006), provided temperatures do not exceed thermal optima. Such changes could improve larval survival and recruitment if larvae can consume sufficient additional food to support the increased energetic demand of developing at a higher temperature. However, recruitment may fail at times and places where food is limited because larvae will be more susceptible to starvation at higher temperatures (Munday et al. 2008a).

The limited evidence available suggests that a 3°C increase in SST would reduce the PLD of larval reef fishes between 12-25% (Munday et al. 2009a). Simulations using coupled biological-physical models indicate that this will tend to reduce the spatial scale of pelagic dispersal. A 20% reduction in PLD for a common reef fish in the Caribbean changed the modal dispersal distance predicted by simulations from ~50km to mostly self-recruitment (10's km) and also reduced the number of larvae dispersing long distances (Munday et al. 2009a). This suggests that reduced PLDs at higher temperatures could reduce population connectivity. However, the effect of reduced PLD on population connectivity was also strongly affected by the dispersion of habitat patches. In areas of high reef density, simulations predicted that local connectivity networks would strengthen with decreased PLD because more larvae would be exchanged between nearby reefs. In contrast, connections between reefs was predicted to be weakened in areas of low reef density. Therefore, the precise effect of reduced PLD on connectivity patterns is likely to differ between locations with contiguous tracks of reef, such as barrier reefs or fringing reefs, and locations with a more fragmented distribution of reefs (Munday et al. 2009a).

As discussed above, geographic range shifts are expected as SST increases. Range limits may increase or contract depending on current distributions and thermal tolerances (Munday et al. 2008a). Most tropical coastal fishes are geographically widespread, but some species have restricted distributions within Australia's tropical zone. At least 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 (Munday et al. 2007). Some of these species will expand their southern limits as temperature increases. The region around 18°S appears to be an important biogeographic boundary for many northern range GBR fishes (M Emslie pers comm), consequently range extension will mostly be south of this region. The speed and extent of range expansions will depend on thermal sensitivity, being faster for more sensitive species (Nilsson et al. 2009), the capacity for dispersal outside the existing geographic range (Booth et al. 2007, Munday et al. 2009a) and ecological interactions with different competitors and predators at more southerly locations.

At least 30 species of fish are restricted to the southern GBR (Munday et al. 2007). The northern range limits of some of these species will shift south as sea temperature increases. One important commercial and recreational species, *Lethrinus miniatus* (sweetlip or redthroat emperor) has an apparent upper thermal limit of about 28°C and is expected to become significantly less abundant in tropical coastal waters as SST increases (Munday et al. 2007). Some species will expand into current-day sub-tropical or temperate locations as temperatures become more favourable at these locations in the future. Some other southern GBR species, however, are confined to coral reefs and are unlikely to persist in non-reef areas, even if temperature become favourable in these

locations. Consequently, the geographic ranges of these species will contract towards the far southern GBR. For these species, smaller ranges would ultimately increase the risk of extinction from other impacts.

Recent evidence suggest that species of tropical reef fishes living at the same location on the GBR differ greatly in their sensitivity to temperature increases. Some species are highly sensitive to a 2-4°C increase in average summer temperature, whereas other species appear to be much more tolerant (Nilsson et al. 2009). These results suggest that range shifts to cooler southern locations will occur rapidly for some species, but more slowly for others species. As a result, local fish communities will change, not just due to the selective effects of habitat loss on different species, but also due to difference in thermal tolerances among species.

Ocean currents and mixing

Changes to major ocean currents, wind-driven surface currents, upwelling and other types of hydrodynamic feature could have important effects on the dispersal and survival of tropical fish larvae (Munday et al. 2009a). However, at this time, the projection of how ocean currents will change lack sufficient confidence and resolution at scales relevant to the ecology of marine fishes to allow any meaningful predictions to be made about the likely impact on tropical coastal fishes (Munday et al. 2008a, 2009a).

It is more certain that there will be greater vertical stratification of the water column, which will tend to reduce nutrient enrichment of surface waters. This may reduce the productivity of plankton communities that are an important food source for many tropical marine fishes, or are the food source for invertebrates that the fish prey on. Planktonic food chains will also be less productive at higher temperatures (McKinnon et al. 2007). At the same time consumers will have increased metabolic demands due to higher metabolic rates at higher temperatures. Consequently, there might be a general decline in the productivity of fish assemblages in tropical waters (Brander 2007). However, changes in productivity will be highly variable and unpredictable. Productivity will probably increase at some locations where local changes to current and upwelling improve nutrient supplies to surface waters.

Extreme weather events and terrestrial runoff

Stronger tropical storms will compound reef degradation caused by coral bleaching and ocean acidification and cause increased disturbances in other habitats. This will affect local fish communities in a range of coastal environments. Changes in rainfall and terrestrial runoff will have greatest effects on nearshore and estuarine species. The ability of fishes to access wetland habitat is influenced by flooding from storms (Sheaves et al. 2006), as well as by tides. A decrease in the frequency of flooding will lead to less regular connectivity (Sheaves 2005). 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 reduce the viability of wetland pools as fish habitats and nurseries. Extended drought allows freshwater pools to dry and saline pools to develop extremely hypersaline conditions (Sheaves et al. 2006). In either case their function as fish habitats is significantly altered. This will reduce the total number of viable pools available, which have already been reduced by the construction of weirs and pasture ponding (Hyland 2002).

Sea level

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Nearshore species will be exposed to coastal inundation and associated habitat changes as a result of the predicted 0.6-0.74 m rise in sea level by 2100. Many coastal environments such as mangroves and seagrass beds have important nursery roles, providing juvenile fish with protection or food resources (Sheaves and Molony 2000). Changes in the extent and proximity of the various habitat types will impact on nursery ground function. The direction and magnitude 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. Sea level rise will influence connectivity among estuaries, estuarine wetlands and freshwater habitats (Sheaves et al. 2006), changing the ability of fish like barramundi, *Lates calcarifer*, to access crucial juvenile habitats. 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, are likely to reduce connectivity. Human responses to prevent inundation of urban areas and farmland as sea level rises will also cause compression of coastal habitats, reducing the habitable area for some nearshore species.

Ocean acidification

The likely effects of ocean acidification on marine fishes are still poorly understood. Acidification will severely affect Australia's coral reefs, especially after 2030 when aragonite saturation levels will become marginal for coral growth (Guinotte et al. 2003). This will contribute significantly to the degradation of reef habitat for fishes. Increased levels of dissolved CO₂ and reduced pH could also potentially affect the physiological performance of some marine fishes (Ishimatsu et al. 2008), especially at the higher water temperatures that will be experienced in the future (Pörtner et al. 2005). To date there is no evidence that elevated CO₂ and reduced pH have a negative effect on the performance of fish larvae, or the development of otoliths (ear bones made of aragonite) (Munday et al. 2009b and unpublished data). However, recent experiments indicate that CO₂ levels (1000ppm) that could be reached by 2100 can exacerbate the sensitivity of some species to increased SST (Munday et al. 2009c) and thus hasten population declines and range shifts towards higher latitudes. Of greater concern is that the levels of CO₂ dissolved in seawater that could occur by 2100 can affect the homing ability of fish larvae and their ability to distinguish between a range of important olfactory stimuli (Munday et al. 2009d). This could seriously affect the replenishment of fish populations and may have implications for the sustainability of reef fish populations.

Major predicted impacts are shown in Table 1 and timelines in Table 2.

Table 1. Predicted impacts of climate change on populations and communities of tropical coastal fishes in Australia and the level of certainty associated with these predictions for 2100. Confidence levels were assigned using the IPCC framework for considering available evidence and expert judgements.

Impact	Physical driver/s	Details	Certainty
Reduced abundances and changes to community composition of reef fishes	Loss of coral cover and declining structural complexity of habitat from coral bleaching, increased storm damage, and reduced calcification rates of corals	Sharp declines in abundance of coral-dependent species and species that prefer to settle near live coral. Longer-term declines in abundances of other species as habitat structure decreases. Increased abundance of some herbivores, small generalist species and rubble-dwellers.	High
Geographic range shifts	Increased temperature	Species distributions will shift south to match preferred temperature ranges. Southern range limits of low-latitude tropical species will tend to expand. Northern range limits of high-latitude tropical species will tend to decline. Geographic ranges will contract for species confined to high-latitude coral reefs .	High
Life history modification	Increased temperature	On average individuals will tend to grow faster during early life, reach smaller maximum sizes, and be shorter lived. Effect size may be small compared to existing natural variation in life history traits.	Moderate
Shift of breeding season	Increased temperature	Breeding of some species will commence earlier. Breeding season may increase at high latitudes.	Moderate
Reproductive decline	Increased temperature	Some low latitude species and species that do not shift the timing of breeding will experience reduced reproductive performance. A mismatch between timing of reproduction and optimum conditions for larvae could develop.	Moderate
Reduced pelagic duration	Increased temperature	Small increases in water temperature will tend to accelerate larval development and competency to settle. Larger increases in temperature may be detrimental to embryonic or larval survival. Changes to larval duration and/or survival probability could influence population connectivity	Moderate
Reduced population replenishment	Ocean acidification	Elevated CO ₂ levels could affect homing ability, habitat selection and predator avoidance of fish larvae.	Low
Reduced population connectivity	Increased temperature and habitat loss	Reduced pelagic larval durations and earlier reef seeking behaviour might reduce the average scale of larval dispersal. Increased habitat fragmentation and smaller population	Low

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		sizes will reduce population connectivity.	
Reduced population genetic diversity	Increased temperature and habitat loss	Strong selection favouring genotypes with tolerance to elevated temperatures and reduced populations sizes from habitat degradation will reduce local genetic diversity.	Low
More extremes in recruitment	Increased temperature and changes in ocean circulation and productivity	Shorter pelagic durations and faster larval growth will tend to reduce larval mortality. However, higher metabolic rates will increase the risk of starvation where food supply is limited. Highly variable and unpredictable – some locations may tend to have better recruitment and others poorer recruitment.	Low
Productivity change	Increased temperature and changes in ocean circulation	Less nutrient enrichment due to greater stratification of surface waters in combination with increased metabolic demands of consumers could reduce productivity at higher trophic levels. Planktonic food chains will be less productive at higher temperatures. Highly variable and unpredictable - productivity may increase at some locations.	Low

Table 2. Observed and predicted impacts of climate change on tropical coastal and demersal marine fishes in Australia. MLD = mixed layer depth

Physical variables	Observed changes	Projected changes	
		2030's	2100's
Temperature	Changes in community structure and declines in abundance of fishes on some coral reefs due to habitat degradation from coral bleaching. Impacts confined to a few reefs that have suffered severe bleaching.	Changes in community structure and declines in abundance of fishes on coral reefs will become more widespread as habitat degrades from coral bleaching, stronger storms and ocean acidification.	Widespread and significant shifts in fish community structure and population declines due to habitat degradation. Loss of diversity (coral-dependent species) and taxonomic distinctness. Some herbivores, small generalist species and rubble-dwellers will increase in abundance.
	Increasing occurrence and persistence of recruits from tropical species in sub-tropical and temperate locations.	Range shift towards higher latitudes evident in the most thermally sensitive species.	Range shifts towards higher latitudes evident for many species. Range area will expand for some species and contract for others. Range contractions will increase the risk of extinction for southern coral-reef endemics.
	Increased growth rate of juvenile Western Gregory at Arolhos Islands associated with at 1.6°C increase in SST over past 25 years	Life history traits of some high latitude populations will shift towards those of the same species in populations at lower latitudes.	Life history traits will shift toward those in populations at low latitudes - smaller maximum size, reduced longevity, faster juvenile growth.
		Reduced reproductive performance in thermally sensitive species. Earlier start to breeding season for some species.	Shifts in the breeding season to match preferred temperature for many species. Significant declines in reproductive performance for thermally sensitive species that do not shift timing of reproduction. Some populations will become unviable at higher latitudes.
			Reduced pelagic duration, possibly leading to greater extremes in recruitment success (more good years and more bad years) and reduced spatial scales of population connectivity.
			Reduced population genetic diversity due to strong selection for thermally tolerant

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Physical variables	Observed changes	Projected changes	
		2030's	2100's
			genotypes.
	Winds, ocean currents, MLD & ocean stratification		Changes in larval dispersal and recruitment patterns at some locations due to changes in currents and upwelling. Highly variable and difficult to predict. Reduced productivity of fish populations due to combined effects of increasing vertical stratification of surface waters, less productive plankton communities (↑ SST and ↓ nutrients). Highly unpredictable – productivity may increase at some locations.
	Precipitation, extreme events, and terrestrial runoff		Greater variation in abundances of nearshore and estuarine species due to reduced function of coastal wetlands as food sources and nursery areas.
	Sea level		Shifts in community structure of nearshore species due to inundation of mangroves and seagrass beds. Loss of juvenile habitat for some species. Impact will be spatially variable and differ greatly among species.
	Acidification (pH)		Impairment of chemosensory ability of larval fishes will affect population replenishment and could lead to population declines in many species. Elevated dissolved CO ₂ levels will exacerbate population declines in thermally sensitive species

Confidence Assessments

Observed Impacts

Confidence levels are given in Table 1. There is good evidence and high consensus that coral bleaching has affected fish community structure at several locations on the Great Barrier Reef and at Scott Reef in WA. Consequently the confidence level is HIGH for this observed impact, although the impacts are currently isolated and not sufficiently widespread to be detected at regional scales (e.g. regions within the Great Barrier Reef). The confidence level is LOW for observed impacts on geographic ranges, life history

traits, and larval recruitment patterns, because there is limited evidence available to date.

Potential impacts by the 2030s and 2100s

There is ample evidence and high consensus that substantial and sustained loss of coral cover and erosion of structural complexity on coral reefs will affect the structure of reef fish communities and lead to reductions in the abundances of some species. Consequently the confidence level is HIGH for this observed impact by 2100. Whether such impact will be widespread by 2030 depends on the accuracy of predictions about the level of degradation on coral reefs by this date, which are still debated. Therefore the certainty of this impact for 2030 is only MODERATE. Potential effects of habitat degradation in non-reefal areas are largely unknown.

Geographic range shifts towards higher latitudes have been observed in many terrestrial and aquatic species and there is high agreement they will occur in most ecosystems as temperatures increase. Range shifts have already been observed in Australia's temperate marine environment and there is some evidence that such shifts may already be underway for tropical species. Consequently the confidence level is HIGH for this predicted impact by 2100. It is uncertain how quickly range shifts will occur for most species, therefore the certainty of this impact for 2030 is only MODERATE.

There is reasonable empirical and experimental evidence to support predictions about change in life histories, shifts in the breeding season, reproductive declines, and reduced pelagic durations in coastal fishes with a 2-3°C increase in SST and consensus in these predictions is moderate. Therefore the confidence for these predictions is MODERATE for 2100. There is less evidence and less consensus that similar trends will be observed with a 1-2°C increase in SST. Therefore the confidence for these predictions is LOW for 2030.

The confidence levels for all other predicted impacts (Table 1) is LOW, both for 2030 and 2100 because there is either limited evidence available to support the predictions, limited agreement, or both.

Adaptation Responses

Some acclimation and adaptation to increased SST will almost certainly occur among Australia's tropical marine fishes, however, the extent to which fishes can withstand predicted increases in SST will vary among species, depending on their current ranges, temperature tolerances, genetic population structure, and generation times. Many tropical species in Australia have geographic ranges spanning temperature gradients of at least 2-3°C. This suggests that there should be considerable potential for acclimation or adaptation to increased SST caused by climate change, especially in southern populations that are currently living at lower temperatures than northern populations of the same species. There is evidence for strong genetic connectivity among populations of some fish species on the GBR (Doherty et al. 1995, Bay et al. 2006), which means that southern populations might already have some tolerance to higher temperatures due to regular genetic input from northern populations. Furthermore, as sea temperature increases, gene flow from northern populations might assist southern populations adapt to the new conditions.

Despite the potential for acclimation and adaptation, populations of some species on the GBR are clearly living close to their thermal optimums. For example, current-day

maximum summer temperatures experienced by populations of the spiny damselfish *A. polyacanthus* at Orpheus Island exceed the thermal optimum for this species (Munday et al. 2008b). Similarly, the aerobic performance of two species of cardinalfishes from Lizard Island (northern GBR) declined by 50% with a 2°C increase in SST above the summer average (Nilsson et al. 2009). Whether these species will be able to adapt quickly enough to rapidly increasing temperatures will depend on their generation times and genetic connectivity with other populations. A more likely scenario for these thermally sensitive species is that northern populations will decline rapidly at SST increases, but the species might become more abundant further south (i.e. rapid shift in geographical distribution and abundance).

Some small-bodied species, such as most gobies, have short generation times that should favour local adaptation over the next 50-100 years. Other species are both long lived and late maturing (e.g. 9-10 years in some groupers and snappers), which would greatly reduce the potential for local adaptation, unless there is considerable genetic input from populations already adapted to warmer waters (Munday et al. 2008a).

There is little prospect of adaptation to habitat loss and degradation. Habitat degradation will also retard adaptation to other climate change impacts by reducing genetic variability within populations and by reducing genetic connectivity between populations (Munday et al. 2008a, 2009). Maintaining and restoring habitat quality for coastal marine fishes should be a major focus for climate change mitigation responses in the coastal environment.

For commercially and recreationally exploited fishes, human adaptation responses should include incorporating larger “safety margins” into harvest levels to provide some insurance from greater variability in population fluctuations and uncertainty about other climate change impacts. In some cases, lower harvest rates will need to be considered because of the possibility that habitat loss and reduced productivity at lower trophic levels (i.e. prey species) will lead to less productive populations of larger predatory species that are favoured by commercial fisheries (Brander 2007, Graham et al. 2007). It should be recognised, however, that the vast majority of tropical marine fishes are not exploited in Australia and for these species the most practical mitigation response (apart from reducing greenhouse gas emissions) is to maintain population resilience by reducing other stresses. Reducing terrestrial runoff, improving water quality, limiting the extent of destructive fishing practices (e.g. benthic trawling), removing barriers to dispersal (e.g. weirs) and considering the impacts that coastal mitigation responses will have on marine fishes are important measures that will assist tropical coastal and benthic fish populations deal with a rapidly changing climate.

Knowledge Gaps

More research is required before we can predict the full ramifications of climate change on tropical coastal fishes and develop better strategies for minimising the impacts (Wilson et al. in press). A range of additional information is needed, including:

- More information on the effects that changes in the physical environment have on the performance, function, and behaviour of marine fishes. Much of the available data comes from temperate species and these results might not be directly applicable to tropical marine fishes.

- Improved projections of how ocean currents and primary productivity will change at regional and local scales for a range of climate change scenarios. The projections are critical for predicting how population dynamics and connectivity patterns will change over the coming century.
- More information on the habitat requirements of fishes, especially around the time of settlement. Understanding the habitat requirements of fishes throughout their life will enable more precise predictions to be made about the long term consequences of declining habitat quality.
- A better understanding of how increased temperature will affect adult reproduction and the development, survival and behaviour of larvae, because little data is available and extrapolations from temperate water species are likely to be unreliable. Moreover, most research on climate impacts for tropical fishes has focussed on small coral reef species and there is an obvious need to consider larger species important to fisheries.
- There are insufficient data on the biology and ecology of fishes in most non-reefal environments. A greater understanding of spatial and temporal variation in distributions and abundances is required to assess potential climate change impacts in these environments.
- Investigations of how ocean acidification will affect the development, survival and behaviour of fishes. Recent evidence suggest that acidification could be a serious threat to marine fishes because it affects behaviour during the early life history. There is very little known about how the interaction between ocean acidification and increased SST will affect marine fishes.
- Research is needed on the capacity for tropical marine fishes to acclimate or adapt to rapid climate change. The potential for adaptation will ultimately determine the consequences of climate change for all ecological communities. Our rudimentary understanding of the potential for adaptation by marine fishes to novel environmental variation is one of the most serious gaps in our knowledge.

Further Information

Suggested further reading

- Munday, P.L., Jones, G.P., Sheaves, M., Williams A.J. and Goby, G. (2007). Vulnerability of fishes of the Great Barrier Reef to climate change. In: *Climate Change and the Great Barrier Reef*. Johnson, J.E. and Marshall, P.A. (eds). Great Barrier Reef Marine Park Authority and Australian Greenhouse Office. Pp 357-391.
- Munday, P.L., Jones, G.P., Pratchett, M.S. and Williams, A.J. (2008). Climate change and the future for coral reef fishes. *Fish and Fisheries* 9: 261-285.
- Munday, P.L., Leis, J.M., Lough, J.M., Paris, C.B., Kingsford M.J., Berumen, M.L. and Lambrechts, J. (2009). Climate change and coral reef connectivity. *Coral Reefs* 28: 379-395.
- Pratchett, M.S., Munday, P.L., Wilson, S.K., Graham, N.A.J., Cinner, J.E., Bellwood, D.R., Jones, G.P., Polunin, N.V.C. and McClanahan, T.R. (2008). Effects of climate-induced coral bleaching on coral-reef fishes: ecological and economic consequences. *Oceanography and Marine Biology Annual Review* 46: 251-296.

- Cheal, A.J., Wilson, S.K., Emslie, M.J., Dolman A.M. and Sweatman, H. (2008). Responses of reef fish communities to coral declines on the Great Barrier Reef. *Marine Ecology Progress Series* 372: 211-223.
- Delean, S. and De'ath, G. (2008). *Spatial and temporal patterns of indicators of reef health on the Great Barrier Reef*. Report to the Marine and Tropical Sciences Research Facility. Reef and Rainforest Research Centre Limited, Cairns (116pp.).
- Wilson, S.K., Graham, N.A.J., Pratchett, M.S., Jones, G.P. and Polunin, N.V.C. (2006). Multiple disturbances and the global degradation of coral reefs: are reef fishes at risk or resilient? *Global Change Biology* 12: 2220-2234.

References

- Allen, G.R. and Swainston R. (1988) *The Marine Fishes of North-Western Australia*. Western Australian Museum.
- Bay, L.K., Crozier, R.H. and Caley, M.J. (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.
- Bellwood, D.R., Hoey, A.S., Ackerman, J.L. and Depczynski, M. (2006) Coral bleaching, reef fish community phase shifts and the resilience of coral reefs. *Global Change Biology* 12: 1587-1594
- Booth, D.J. and Beretta, G.A. (2002) Changes in a fish assemblage after a coral bleaching event. *Marine Ecology Progress Series* 245: 205-212.
- Booth, D.J. 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.
- Booth, D.J., Figueira, W.F., Gregson, M.A., Brown, L. and Beretta, G. (2007) Occurrence of tropical fishes in temperate southeastern Australia: Role of the East Australian Current. *Estuarine Coastal and Shelf Science* 72: 102-114.
- Brander, K. (2007) Global fish production and climate change. *Proceedings of the National Academy of Sciences USA* 104: 19709–19714.
- Cheal, A.J., Delean, S., Sweatman, H. and Thompson, A.A. (2007) Spatial synchrony in coral reef fish populations and the influence of climate. *Ecology* 88: 158-169.
- Cheal, A.J., Wilson, S.K., Emslie, M.J., Dolman A.M. and Sweatman, H. (2008) Responses of reef fish communities to coral declines on the Great Barrier Reef. *Marine Ecology Progress Series* 372: 211-223.
- Choat, J.H. and Robertson, D.R. (2002) Age-Based Studies. In: *Coral Reef Fishes. Dynamics and Diversity in a Complex Ecosystem* (ed P.F. Sale) Academic Press, San Diego, pp. 57-80.
- Choat, J.H. and Russell, B.C. (2009) The fish assemblages of the Great Barrier Reef: their diversity and origin. In: *The Great Barrier Reef; Biology, Environment and Management* (eds. Hutchings, P, Kingsford, M., Hoegh-Guldberg, O.) Springer and CSIRO Publishing, Dordrecht and Collingwood, pp. 327-342.
- Delean, S. and De'ath, G. (2008) *Spatial and temporal patterns of indicators of reef health on the Great Barrier Reef*. Report to the Marine and Tropical Sciences Research Facility. Reef and Rainforest Research Centre Limited, Cairns (116pp.).
- Doherty, P.J., 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.
- Donelson, J.M., Munday, P.L., McCormick M.I., Pankhurst N.W. and Pankhurst P.M. (2010) Effects of elevated water temperature and food availability on the reproductive performance of a coral reef fish. *Marine Ecology Progress Series*, in

- press.
- Donner, S.D., Skirving, W.J., Little, C.M., Oppenheimer, M. and Hoegh-Guldberg, O. (2005) Global assessment of coral bleaching and required rates of adaptation under climate change. *Global Change Biology* 11: 2251-2265.
- Edwards, M. and Richardson, A.J. (2004) Impact of climate change on marine pelagic phenology and trophic mismatch. *Nature* 430: 881-884.
- Figueira, W.F. and Booth, D.J. (2009) Increasing ocean temperatures allow tropical fishes to survive over winter in temperate waters. *Global Change Biology*, in press.
- Gagliano, M., McCormick, M.I. and Meekan, M.G. (2007) Temperature-induced shifts in selective pressure at a critical developmental transition. *Oecologia* 152: 219-225.
- Graham, N.A.J., Wilson, S.K., Jennings, S., Polunin, N.V.C., Bijoux, J.P. and Robinson, J. (2006) Dynamic fragility of oceanic coral reef ecosystems. *Proceedings of the National Academy of Sciences USA* 103: 8425-8429.
- Graham, N.A.J., Wilson, S.K., Jennings, S., Polunin, N.V.C., Robinson, J., Bijoux, J.P., and Daw, T.M. (2007) Lag effects in the impacts of mass coral bleaching on coral reef fish, fisheries, and ecosystems. *Conservation Biology* 21: 1291-1300
- Graham, N.A.J., McClanahan, T.R., MacNeil, M.A., Wilson, S.K., Polunin, N.V.C., Jennings, S., Chabanet, P., Clark, S., Spalding, M.D., Letourneur, Y., Bigot, L., Galzin, R., Öhman, M.C., Garpe, K.C., Edwards, A.J. and Sheppard C.R.C. (2008) Climate warming, marine protected areas and the ocean-scale integrity of coral reef ecosystems. *PLoS ONE* 3, e3039.
- Great Barrier Reef Marine Park Authority (2007) Great Barrier Reef coral bleaching surveys 2006 : undertaken as a part of the climate change coral bleaching response plan, March-April 2006. Research publication No. 87. Great Barrier Reef Marine Park Authority, Townsville.
- Green, B.S. 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.
- Guinotte, J.M., Buddemeier, R.W. and Kleypass, J.A. (2003) Future coral reef habitat marginality: temporal and spatial effects of climate change in the Pacific basin. *Coral Reefs* 22: 551-558.
- Halford A.R. and Caley, M.J. (2009) Towards an understanding of resilience in isolated coral reefs. *Global Change Biology*, doi: 10.1111/j.1365-2486.2009.01972.x
- Halford, A., Cheal, A.J., Ryan, D. and Williams, D.M. (2004) Resilience to large-scale disturbance in coral and fish assemblages on the Great Barrier Reef. *Ecology* 85: 1892-1905.
- Hickling, R., Roy, D.B., Hill, J.K., Fox, R. and Thomas, C.D. (2006) The distributions of a wide range of taxonomic groups are expanding polewards. *Global Change Biology* 12: 450-455.
- Hilder, M.L. and Pankhurst, N.W. (2003) Evidence that temperature change cues reproductive development in the spiny damselfish, *Acanthochromis polyacanthus*. *Environmental Biology of Fishes* 66: 187-196.
- Hoegh-Guldberg, O. (1999) Climate change, coral bleaching and the future of the world's coral reefs. *Marine and Freshwater Research* 50: 839-866.
- Hoegh-Guldberg, O., Mumby, P.J., Hooten, A.J., Steneck, R.S., Greenfield, P., Gomez, E., Harvell, C.D., Sale, P.F., Edwards, A.J., Caldeira, K., Knowlton, N., Eakin, C.M., Iglesias-Prieto, R., Muthiga, N., Bradbury, R.H., Dubi, A. & Hatziolos, M.E. (2007) Coral reefs under rapid climate change and ocean acidification. *Science* 318: 1737-1742.
- Hyland, S.J. (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.
- Ishimatsu, A. Hayashi, M. and Kikkawa, T. (2008) Fishes in high-CO₂, acidified oceans. *Marine Ecology Progress Series* 373: 295-302.
- Jones, G.P., McCormick, M.I., Srinivasan, M. and Eagle, J.V. (2004) Coral decline threatens fish biodiversity in marine reserves. *Proceedings of the National Academy of Sciences of the United States of America* 101: 8251-8253.
- Leis, J.M. (1991) The pelagic stage of reef fishes: The larval biology of coral reef fishes. In: *The Ecology of Fishes on Coral Reefs* (ed P.F. Sale) Academic Press, San Diego, pp. 183-230.
- Marshall, P.A. and Baird, A.H. (2000) Bleaching of corals on the Great Barrier Reef: differential susceptibilities among taxa. *Coral Reefs* 19: 155-163.
- Meekan, M.G., Carleton, J.H., McKinnon, A.D., 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.
- McCormick, M.I. and Molony, B.W. (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.
- McKinnon, A.D., Richardson, A.J., Burford, M.E. and Furnas, M.J. (2007) Vulnerability of Great Barrier Reef plankton to climate change. In: *Climate Change and the Great Barrier Reef* (eds J.E. Johnson and P.A. Marshall) Great Barrier Reef Marine Park Authority and Australian Greenhouse Office, Townsville, pp. 121-152.
- Munday, P.L. (2004) Habitat loss, resource specialization, and extinction on coral reefs. *Global Change Biology* 10: 1642-1647.
- Munday, P.L., Jones, G.P., Sheaves, M., Williams A.J. and Goby, G. (2007) Vulnerability of fishes of the Great Barrier Reef to climate change. In: *Climate Change and the Great Barrier Reef*. Johnson, J.E. and Marshall, P.A. (eds) Great Barrier Reef Marine Park Authority and Australian Greenhouse Office. Pp 357-391.
- Munday, P.L., Jones, G.P., Pratchett, M.S. and Williams, A.J. (2008a) Climate change and the future for coral reef fishes. *Fish and Fisheries* 9, 261-285.
- Munday, P.L., Kingsford, M., O'Callaghan, M. and Donelson, J.M. (2008b) Elevated temperature restricts growth potential of the coral reef fish *Acanthochromis polyacanthus*. *Coral Reefs* 27: 927-931.
- Munday, P.L., Leis, J.M., Lough, J.M., Paris, C.B., Kingsford M.J., Berumen, M.L. and Lambrechts, J. (2009a) Climate change and coral reef connectivity. *Coral Reefs* 28: 379-395.
- Munday, P.L., Donelson, J.M., Dixon, D.L. and Endo, G.G. K. (2009b) Effects of ocean acidification on the early life history of a tropical marine fish. *Proceedings of the Royal Society London B* 276: 3275-3283.
- Munday, P.L., Crawley, N. and Nilsson, G.E. (2009c) Interacting effects of elevated temperature and ocean acidification on the aerobic performance of coral reef fishes. *Marine Ecology Progress Series* 388: 235-242.
- Munday, P.L., Dixon, D.L., Donelson, J.M., Jones, G.P., Pratchett, M.S., Devitsina, G.V. and Døving, K.B. (2009d) Ocean acidification impairs olfactory discrimination and homing ability of a marine fish. *Proceedings of the National Academy of Sciences USA* 106: 1848-1852.
- Nilsson, G.E., Crawley N., Lunde I.G. and Munday P.L. (2009) Elevated temperature reduces the respiratory scope of coral reef fishes. *Global Change Biology* 15: 1405-1412.
- O'Connor, M.I., Bruno, J.F., Gaines, S.D., Halpern, B.S., Lester, S.E., Kinlan, B.P. and

- Weiss, J.M. (2007) Temperature control of larval dispersal and the implications for marine ecology, evolution, and conservation. *Proceedings of the National Academy of Sciences USA* 104: 1266-1271.
- Pankhurst, N.W. and Porter, M.J.R. (2003) Cold and dark or warm and light: variations on the theme of environmental control of reproduction. *Fish Physiology and Biochemistry* 28: 385-389.
- Parmesan, C. (2006) Ecological and evolutionary responses to recent climate change. *Annual Review of Ecology Evolution and Systematics* 37: 637-669.
- Portner, H.O., Langenbuch, M., Michaelidis, B. (2005) Synergistic effects of temperature extremes, hypoxia, and increases in CO₂ on marine animals: From Earth history to global change. *Journal of Geophysical Research-Oceans* 110: C09S10 doi:10.1029/2004JC002561.
- Pratchett, M.S., Wilson, S.K., Baird, A.H. (2006) Declines in the abundance of Chaetodon butterflyfishes following extensive coral depletion. *Journal of Fish Biology* 69: 1269-1280.
- Pratchett, M.S., Munday, P.L., Wilson, S.K., Graham, N.A.J., Cinner, J.E., Bellwood, D.R., Jones, G.P., Polunin, N.V.C. and McClanahan, T.R. (2008) Effects of climate-induced coral bleaching on coral-reef fishes: ecological and economic consequences. *Oceanography and Marine Biology Annual Review* 46: 251-296.
- Randall, J.E., Allen, G.R. and Steene, R.C. (1997) *Fishes of the Great Barrier Reef and Coral Sea*. University of Hawaii Press, USA.
- Robertson, D.R., Ackerman, J.L., Choat, J.H., Posada, J.M. and Pitt, J. (2005) Ocean surgeonfish *Acanthurus bahianus*. I. The geography of demography. *Marine Ecology Progress Series* 295: 229-244.
- Sheaves, M.J. (2005) Nature and consequences of biological connectivity in mangrove systems. *Marine Ecology Progress Series* 302: 293-305.
- Sheaves, M.J. (2006) Is the timing of spawning in sparid fishes a response to sea temperature regimes? *Coral Reefs* 25: 655-669.
- Sheaves, M. and Molony, B. (2000) Short-circuit in the mangrove food chain. *Marine Ecology Progress Series* 199: 97-109.
- Sheaves, M.J., Collins, W., Houston, P., Dale, A., Reville, R., Johnston, W.A. 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.
- Sponaugle, S., Grorud-Colvert, K. and Pinkard, D. (2006) Temperature-mediated variation in early life history traits and recruitment success of the coral reef fish *Thalassoma bifasciatum* in the Florida Keys. *Marine Ecology Progress Series* 308: 1-15.
- Wilkinson, C. (2004) *The Status of Coral Reefs of the World: 2004*. Australian Institute of Marine Science.
- Wilson, D.T. and Meekan, M.G. (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.
- Wilson, S.K., Fisher, R., Pratchett, M.S., Graham, N.A.J., Dulvy, N.K., Turner, R., Cakacaka, A., Polunin, N.V.C. and Rushton S.P. (2008a) Exploitation and habitat degradation as agents of change within coral reef fish communities. *Global Change Biology* 14: 2796-2809.
- Wilson, S.K., Burgess, S.C., Cheal, A.J., Emslie, M., Fisher, R., Miller, I., Polunin, N.V.C. and Sweatman, H.P.A. (2008b) Habitat utilization by coral reef fish:

- implications for specialists vs. generalists in a changing environment. *Journal of Animal Ecology* 77: 220-228.
- Wilson, S.K., Dolman, A.M., Cheal, A.J., Emslie, M., Pratchett, M.S. and Sweatman, H.P.A. (2009) Maintenance of fish diversity on disturbed coral reefs. *Coral Reefs* 28: 3-14.
- Wilson, S.K., Graham, N.A.J., Pratchett, M.S., Jones, G.P. and Polunin, N.V.C. (2006) Multiple disturbances and the global degradation of coral reefs: are reef fishes at risk or resilient? *Global Change Biology* 12: 2220-2234.
- Wilson, S.K., Adjeroud, M., Bellwood, D.R., Berumen, M.L., Booth, D., Bozec, Y-M., Chabanet, P., Cheal, A., Cinner, J., Depczynski, M., Feary, D.A., Gagliano, M., Graham, N.A.J., Halford, A.R., Halpern, B.S., Harborne, A.R., Hoey, A.S., Holbrook, S., Jones, G.P., Kulbiki, M., Letourneur, Y., De Loma, T.L., McClanahan, T., McCormick, M.I., Meekan, M.G., Mumby, P.J., Munday, P.L., Öhman, M.C., Pratchett, M.S., Riegl, B., Sano, M., Schmitt, R.J., Syms, C. Critical knowledge gaps in current understanding of climate change impacts on coral reef fishes. *Journal of Experimental Biology*, in press.