Tropical Coastal Fish

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What is happening

New research suggests that some species have a greater capacity to acclimate to rising temperatures than previously thought; however whether such acclimation capacity is widespread in tropical marine fishes, and whether some critical processes (e.g. reproduction) remain significantly impaired, is unknown.

What is expected

In addition to effects of habitat degradation, warmer ocean temperatures will cause distribution shifts in some tropical fishes, increasing the geographic ranges of some species and decreasing the ranges of others, including some commercially important species.

What we are doing about it

Experimental and observational work is underway to investigate the adaptive capacity of tropical fish.

Summary

Climate change is expected to affect populations and communities of tropical 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 projected 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, ocean acidification and more intense storms. There is good evidence and strong 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 are expected to 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 are projected to 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 also have very significant effects on populations and communities of coastal fishes in the longer term. There are a many critical knowledge gaps in our understanding of the effect of climate change on tropical marine fish, including how predicted effects on individuals and populations will scale-up to influence community structure and function, 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 likely to reduce the sustainability of fish populations.

Introduction

Australia has over 1.5 million km^2 of tropical coastal waters (territorial area within the continental shelf) extending from Queensland and the Great Barrier Reef (GBR) 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). Some 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 is expected to affect individuals, 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, Pratchett et al. 2011a). 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 spawning, reproductive output, larval development, population connectivity and geographic distributions (Table 1). The effects of climate change on food supply and habitat quality are projected to have further significant effects on marine fishes (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, 2011b) 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 are also expected to 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). Over the past few years there has been increased research into the effects that changes to the physical environment have on the ecology and biology of tropical marine fishes. However, the number of studies remains low and most experimental research has involved small, site-attached coral reef species. The relevance of these studies to larger, mobile fish species is still uncertain. Although the confidence in most projections about the impact of climate change on Australia’s tropical coastal fishes remains moderate-low, and unforseen impacts are likely to occur, there have been significant advances in our understanding of some climate change threats (e.g. ocean acidification). The level of certainty regarding other impacts has also improved since the first assessment in 2009

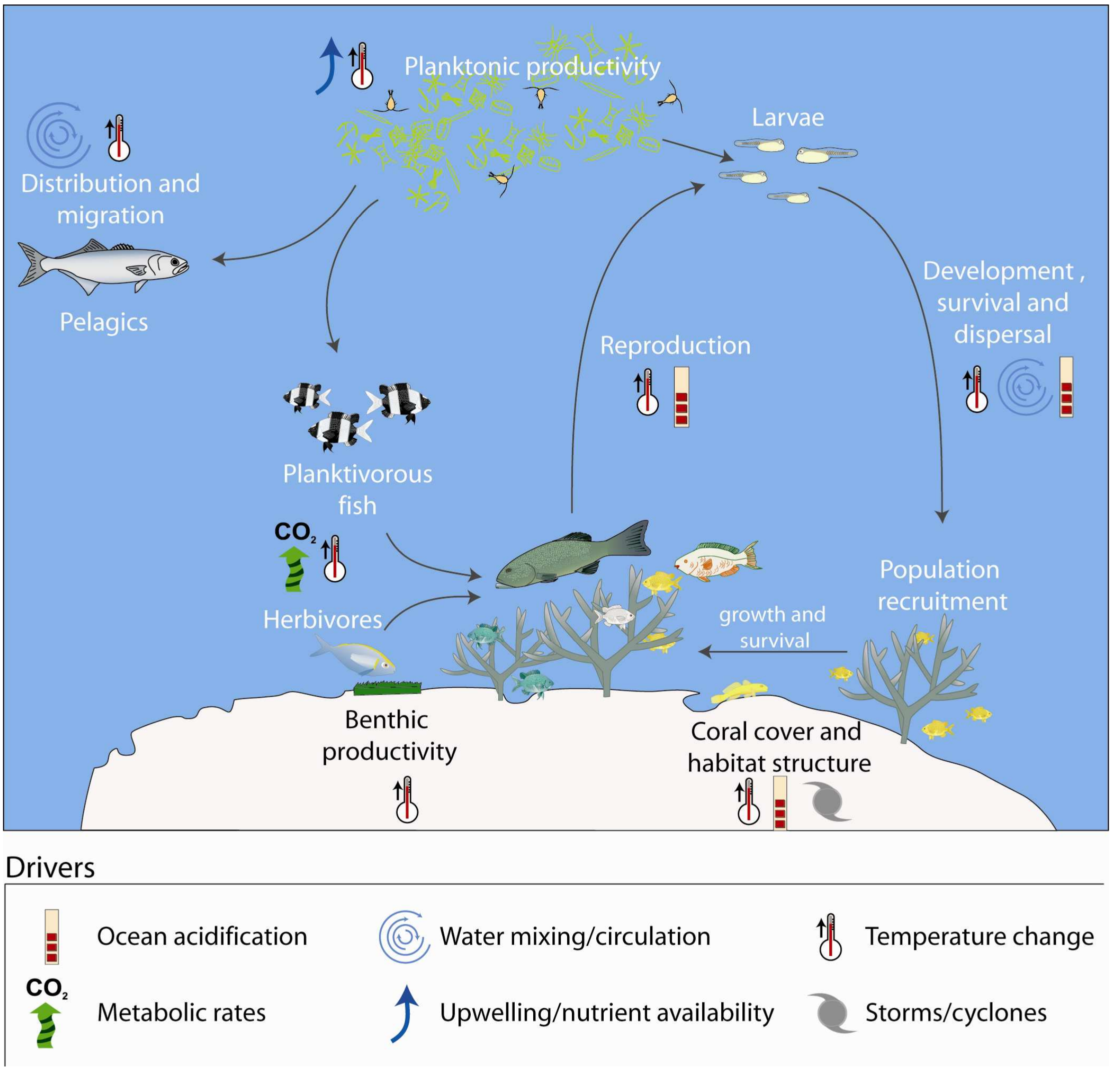

Figure 1. *The potential impacts of climate change on populations and communities of tropical coastal fishes will depend on complex interactions between changes in the physical environment (e.g. changes in SST, currents and upwelling, storms, ocean pH), physiological and behavioural responses of fishes at different life history stages, energy transfer between trophic levels, and the effect of altered 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 declines further if the effects of coral bleaching interact with other disturbances that kill live coral, such as outbreaks of crown of thorns starfish, increasingly severe storms, or terrestrial pollution. The interacting effects of climate change and other stresses to reef habitats (Pratchett et al. 2011b) 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 their diet, habitat or settlement (Wilson et al. 2006, Pratchett et al. 2008, Emslie et al. 2011). 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. Approximately 42% of GBR reefs bleached to some extent in 1998, although the 2002 bleaching event was more extensive (Berkelmans et al. 2004). In 2002, approximately 54% of GBR 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. Scott Reef in Western Australia suffered severe bleaching in 1998, with an 80% reduction in coral cover recorded (Smith et al. 2008). A localised 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. Although severe bleaching events have occurred on Australia’s coral reefs, there has also been significant post-bleaching recovery (Smith et al. 2008; Osborne et al. 2011; Pratchett et al. 2011b).

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 on the GBR. Since the mid 1990’s outbreaks of crown-of-thorns starfish and severe storms appear to have caused most of the coral mortality on the GBR and climate-induced coral bleaching has so far contributed relatively little to observed coral loss (Osborne et al. 2011; Pratchett et al. 2011b). Nevertheless, sustained and ongoing climate change will have increasing impacts in coming years, including increases in the intensity and frequency of coral bleaching (Hoegh-Guldberg 1999, Donner et al. 2005). Aside from causing declines in coral abundance, selective effects of bleaching and stronger storms are likely to cause changes in the structure of coral assemblages, which in turn will affect fish assemblages (e.g., Berumen and Pratchett 2006).

Averaged across all 48 reefs surveyed by the LTMP, there was little change in species richness and diversity of fish communities sampled between 1993-2007 (Delean and De’ath 2008). Similarly, there was 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 were, however, large and important changes in fish abundance and community structure at specific reefs where coral cover had declined significantly (Halford et al. 2004, Cheal et al. 2008). In the most comprehensive study to date, Cheal et al. (2008) found that although fish diversity was not affected on seven reefs that suffered over 75% coral loss from a variety of disturbances between 1995-2005, there were major changes in fish community structure. Changes included increases in abundance of large herbivores and decreases in abundance of both coral-dependent fishes and also some 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 occurs more frequently in the future (Table 2).

The structure of fish communities at Scott Reef in Western Australia also changed substantially following the 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 (butteflyfishes 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. Recent surveys indicate further recovery to coral and fish communities at Scott Reef (Anon 2010; Smith pers. com.), although fish communities are now characterised by species with more generalist diet and habitat requirements than those before the bleaching, and abundances of mid-sized fishes have increased substantially, possibly due to overfishing of sharks and other top predators (Travers pers. com.; Meekan pers. com.).

A range of other impacts on tropical coastal fishes are expected (Table 1) and there are indications that some of these are already occurring. Geographic range shifts are a common response of animals to climate change, 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 projected 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 these fish, 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). There have also been increasing anecdotal reports of larger tropical species being sighted and caught as far south as Perth in Western Australia in recent years (Wilson pers. com.). The apparent increase in larger, mobile, tropical species, is associated with a strong La Nina pattern and anomalously high water temperatures (4-5°C above summer averages) extending into higher latitudes (Pearce et al. 2011). These observations indicate that range shifts by tropical species are already underway.

Many tropical marine fishes have large latitudinal ranges that extend across temperature gradients of 3-4^{o}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^{o}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 altering in response to climate change.

Finally, small increases in SST are expected to increase larval survival of marine species by reducing the duration of the pelagic phase (O'Connor et al. 2007). Consistent with this projection, Cheal et al. (2007) found that large population increases of damselfishes on the GBR often followed elevated SST associated with El Niño events. However, higher temperatures have not been beneficial to larval supply in other locations. In a long-term study in French Polynesia, larval supply of coral reef fishes declined by >50% below average during the 1997-98 El Niño, when average SST was 3.5°C above the mean, and increased nearly 250% during La Niña years, when temperatures were almost 2°C below the mean (Lo-Yat et al. 2012). Increased larval supply during La Niña years was correlated with increased ocean productivity (chlorophyll-a). These results suggest that increased temperatures can have negative effects on affect both the reproductive output by adults and the survival of larvae in the plankton, leading to a reduced supply of larvae to replenish benthic populations.

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^{o}C increase in SST by 2030 and 2-3^{o}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, Pankhurst and Munday 2011). At least some tropical coastal fishes appear to be closely adapted to the local thermal environment (Pankhurst and Porter 2003, Nilsson et al. 2009, Donelson et al. 2010), 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^{o}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). Pathways for synthesis of reproductive hormones are temperature sensitive in fish (Pankhurst and Munday 2011) and it is possible that reproduction may be severely curtailed by rising water temperature, even in species that exhibit some capacity for acclimation to higher temperatures over a number of generations (Donelson et al. 2011, 2012). 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 spawning season is thought to be cued by temperature in many tropical fish 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 spawning (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 their spawning cycle as SST increases.

Early developmental stages of reef fishes are particularly sensitive to temperature changes. Small temperature increases may 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, Lo-Yat et al. 2011).

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 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 weakened in areas of low reef density. Therefore, projecting the effect of reduced PLD on connectivity patterns is challenging, and the outcome is likely to differ between locations with contiguous tracts 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^{o}S appears to be an important biogeographic boundary for many fish in the northern GBR (M Emslie pers comm), Consequently, most range extensions are likely to be south of this region. The speed and extent of range expansions will depend on: (1) thermal sensitivity, being faster for more sensitive species (Nilsson et al. 2009), (2) the capacity for dispersal outside the existing geographic range (Booth et al. 2007, Munday et al. 2009a) and (3) 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 SST increases. One important commercial and recreational species, *Lethrinus miniatus* (sweetlip or redthroat emperor) has an apparent upper thermal limit of about 28ºC and is expected to become significantly less abundant in tropical coastal waters (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.

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^{o}C increase in average summer temperature, whereas others 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. There is also evidence that populations on the southern GBR have greater capacity to cope with elevated temperatures than populations of the same species on the northern GBR (Gardiner et al. 2010). Therefore, northern populations are at greatest risk of decline, even if they experience a smaller increase in SST compared with southern populations.

Finally, nearshore and estuarine fishes show consistent assemblage composition across large latitudinal gradients, indicating they are adapted to highly variable environments, and so are likely to be less affected by physical changes such as rising SST than fish with more restricted physical tolerances.

Ocean currents and mixing

Changes to major ocean currents, wind-driven surface currents, upwelling and other types of hydrodynamic features could have important effects on the dispersal and survival of tropical fish larvae (Munday et al. 2009a, Lo-Yat et al. 2011). However, at this time, the projections of how ocean currents will change lack sufficient confidence and resolution at scales relevant to the ecology of marine fishes to allow meaningful predictions to be made about the likely impact on tropical coastal fishes..

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, Cheung et al. 2010). 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 beside coral reefs. Such changes affect local fish communities in a range of coastal environments. Changes in rainfall and terrestrial runoff are expected to 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 would 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, exacerbating the reduction already occurring through the construction of weirs and pasture ponding (Hyland 2002).

Sea level

Nearshore species will be exposed to coastal inundation and associated habitat changes as a result of the projected 0.6-0.74 m rise in sea level by 2100. Many coastal environments such as mangroves and seagrass beds, provide juvenile fish with protection or food resources (Sheaves and Molony 2000). Changes in the extent and proximity of the various habitat types would affect their function as nursery grounds for a range of commercially valuable fish species.. The direction and magnitude of this impact is likely to vary spatially, determined by the details of specific habitat change, and is likely to depending on the specific requirements of different species. 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 is expected to enhance connectivity between habitats that are normally isolated at low tide. However, human responses to prevent inundation of urban areas and farmland as sea level rises could also cause compression of coastal habitats, reducing connectivity and the habitable area for some nearshore fish species.

Ocean acidification

Acidification of the ocean is expected to significantly affect Australia’s coral reefs, especially after 2030 when aragonite saturation levels are projected to become marginal for coral growth (Guinotte et al. 2003). As a result, significant degradation of reef habitat for fishes is expected. A further concern is that increased levels of dissolved CO_2 could affect the physiological performance and behaviour of some marine fishes (Ishimatsu et al. 2008, Munday et al. 2009c,d, Nilsson et al. 2012), especially at projected higher water temperatures (Pörtner et al. 2005).Studies in Australia have found no evidence that elevated CO_2 levels have a direct negative effect on the growth, survival or swimming performance of larval or juvenile reef fish (Munday et al. 2009b, 2011a).. Similarly the development of otoliths (ear bones made of aragonite) appears to unaffected by CO_2 levels likely to be experienced in surface-ocean waters over the next 50-100 years (Munday et al. 2011a,b) However, nearly all the research to date has concerned small demersal-spawning reef fishes, which might be adapted to variable CO_2 levels, especially during early development. It is possible that pelagic species and broadcast spawners are more susceptible to higher CO_2 levels during early development (Munday et al. 2008a, 2011a,b).

Of greater concern is that CO_2 levels projected to occur by 2100 can impair sensory functions and alter a broad suite of behaviours in larval, juvenile and adult fishes. Changes include increased boldness and activity (Munday et al. 2010), loss of behavioural lateralization (Domenici et al. 2012), altered auditory preferences (Simpson et al. 2011), inability to learn (Ferrari et al. 2012), and impaired olfactory function (Munday et al. 2009d), the latter making larval fish attracted to odours they normally avoid, including smells from predators and unfavourable habitats (Munday et al. 2009d, 2010, Dixson et al. 2010). These behavioural alterations significantly increase mortality of fish in natural reef habitat, with potentially far-reaching implications for population replenishment, community structure and ecosystem function (Munday et al. 2010, Ferrari et al. 2011a,b). New research has found that these diverse behavioural and sensory effects are caused by interference with neurotransmitter function by changed ion concentrations in the tissues of fish exposed to high CO_2, (Nilsson et al. 2012). Importantly, effects are manifest in both larval and adult reef fishes at the CO_2 levels (600-700 µatm CO_2) that are projected to occur by 2100 on the IS92a emissions scenario (Munday et al. 2010, Simpson et al. 2011, Devine et al. 2012), thus increased CO_2 concentrations could be a serious threat to marine fishes in the later part of the century.

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

Table 1. *Projected 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, more intense storms, 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

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, more intense storms, 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
Behavioural and sensory impairment	Ocean acidification	Elevated CO_2 levels could affect homing ability, habitat selection and predator avoidance of larval, juvenile and adult fish.	High
More extremes in recruitment	Increased temperature and changes in primary productivity and ocean circulation	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.	Moderate
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.	Moderate
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 sizes will reduce population connectivity.	Low
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

Table 2. *Observed and projected 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 or locations 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, more intense 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. Increased reports of tropical species in temperate locations	Range shift towards higher latitudes evident in the most thermally sensitive and mobile 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 Abrolhos Islands associated with 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. However changes will be difficult to distinguish from natural variation	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).
			Reduced population genetic diversity due to strong selection for thermally tolerant 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 (elevated $p\mathrm{CO}_2$)			Impairment of sensory ability and changed behaviour of larval fishes will affect population replenishment and could lead to population declines in many species. Cognitive function of fish is impaired at CO_2 levels predicted to occur by 2100
			Elevated dissolved CO_2 levels will exacerbate population declines in thermally sensitive species

Observed Impacts: Confidence Assessments

Confidence levels are given in Table 1. There is good evidence and strong 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 and it is difficult to distinguish climate change effects from natural variation (e.g. El Niño).

Potential impacts by the 2030s and 2100s: Confidence Assessments

There is ample evidence and strong consensus that substantial and sustained loss of coral cover, changes in coral composition, 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 that such changes will be evident 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-reef 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 projections about changes in life histories, shifts in the spawning season, reproductive declines, and reduced pelagic durations in coastal fishes with a 2-3^{o}C increase in SST and consensus in these projections is moderate. Therefore the confidence for these projections is MODERATE for 2100. There is less evidence and less consensus that similar trends will be observed with a 1-2^{o}C increase in SST. Thus, the confidence for these predictions is LOW for 2030. Similarly, there is now sufficient empirical and theoretical evidence to support projections about increased variability in recruitment patterns and an overall reduction in productivity by 2100. Therefore the confidence for these projections is MODERATE for 2100. It is unlikely that any trends in these variable could be distinguished from natural variation by 2030. Therefore the confidence for these projections is LOW for 2030.

There is now strong experimental evidence that CO_2 levels projected to occur by 2100 under the IS92a/A2 emissions scenario (>600 ppm CO_2) impair cognitive function in reef fishes, leading to maladaptive behaviour. Therefore, the confidence level is HIGH for this impact by 2100. CO_2 levels will not be sufficiently high (e.g. >600 ppm CO_2) by 2030 to cause behavioural problems in marine fish.

The confidence levels for other predicted impacts (Table 1) are LOW, both for 2030 and 2100 because there is either limited evidence available to support the projections, 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 projected increases in SST will vary among species, depending on their current ranges, temperature tolerances, genetic population structure, and generation times. Many tropical fish species in Australia have geographic ranges spanning temperature gradients of at least 2-3^{o}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 (Gardiner et al. 2010). 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 appear to be living close to their thermal optimums. For example, a 1.5°C increase in average summer temperatures causes significant declines in growth and reproductive output of the spiny damselfish *A. polyacanthus* from Orpheus Island (Munday et al. 2008b, Donelson et als. 2010). Similarly, the aerobic performance of two species of cardinalfishes from Lizard Island (northern GBR) declined by 50% with a 2^{o}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 as 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 that are already adapted to warmer waters (Munday et al. 2008a).

It has recently been discovered that some reef fishes may have more capacity for thermal acclimation than previously thought. Aerobic performance of juvenile *A. polyacanthus* was significantly reduced in warmer water, but not if the parental generation had also been exposed to higher temperatures their whole life (Donelson et al. 2012). This indicates that acclimation of some physiological traits to higher temperatures may occur in some species as the climate warms over coming decades.

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 (Pratchet et al. 2011a).

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 revised 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). Limiting fishing pressure on larger mobile species, and species that perform key ecological roles is also important as many of these species are more vulnerable to increased fishing pressure than climate change (Graham et al. 2011). It should be recognised, however, that the vast majority of tropical marine fishes in Australia are not exploited and the most practical mitigation response for these species (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. 2010). 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 are likely to change at regional and local scales for a range of climate change scenarios. The projections are critical for understanding how population dynamics and connectivity patterns may 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 is expected to affect adult reproduction and the development, survival and behaviour of larvae, because relatively little data are 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 affects the development, survival and behaviour of broadcast spawning and pelagic fishes. Elevated CO_2 levels do not appear to directly affect the growth and survival of small demersal fishes, but larger pelagic species might be more sensitive to future rises in CO_2. There is now ample evidence that high CO_2 levels could be a serious threat to marine fishes because they affect cognitive function and behaviour of marine fish. However, very little is known about how increased SST and CO_2 might interact to affect marine fishes.
- Much more research is needed on the capacity for tropical marine fishes to acclimate or adapt to rapid climate change. New research suggests that some species have a greater capacity to acclimate to rising temperatures than

previously though possible; however if such acclimation capacity is widespread in tropical marine fishes, and whether some critical processes (e.g. reproduction) remain significantly impaired, is unknown. The potential for adaptation will ultimately determine the consequences of climate change for all ecological communities. Our rudimentary understanding of the potential for acclimation and adaptation by marine fishes to novel environmental variation is one of the most serious gaps in our knowledge.

Observation Programs

The AIMS Long Term Monitoring Program (LTMP) has surveyed 47 reefs in the Great Barrier Reef (GBR) annually since 1993. A team of trained divers surveys fishes by underwater visual census and records corals and other benthic organisms along the same sections of reef at each visit. Fishes from a list of 191 species, representing 10 families, are counted at three sites on each reef. Fish surveys are conducted in 6 sectors, from Cooktown/Lizard Island in the north to the Capricorn Bunkers in the south. Information is available on the internet and is updated after each visit (http://www.aims.gov.au/docs/research/monitoring/reef/latest-surveys.html). Status reports are produced approximately every two years (http://www.aims.gov.au/docs/research/monitoring/reef/status-reports.html). The LTMP also provides situational awareness on threats, such as coral bleaching and crown of thorns starfish outbreaks. AIMS has been monitoring fish and coral communities on Scott Reef in Western Australia on a semi-regular basis since 1994. Summary information is presented in occasional reports.

University researchers have monitored fish populations at specific locations in tropical Australia for various periods of time. James Cook University has surveyed fish populations on 3 reefs in the Townsville region on a biannual basis since 2002, and Western Australian researchers are also active from Rottnest island north.

Fisheries Queensland has conducted fishery independent surveys since 2005/6 to determine annual trends in abundance, length and age structure of two commercially important reef fishes on the GBR. Data are available in annual status reports.

Observation Programs for Climate Change

Although reef fishes on the GBR are monitored annually by the AIMS LTMP, and to a limited extent by some other programs, there is little monitoring of non-reef and inshore fishes. A monitoring program for key species would be beneficial. Similarly, there is currently insufficient monitoring of fish populations throughout NW Australia. In all areas, more robust estimates of annual catch and effort trends for demersal fish species from all sectors (commercial and recreational) are necessary.

Greater resolution of spatial and temporal variation of key physical parameters, including sea surface temperature, pH, pCO_2, productivity, and surface currents is required.

An improved understanding of the capacity for fish populations to adjust to changes in environmental conditions over years to decades is urgently required.

Further Information

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