CoastAdapt

Climate change impacts on coastal fisheries and aquaculture

Ryan Pearson and Rod Connolly

Impact Sheet 7

www.coastadapt.com.au

Contents

Wild catch fisheries and aquaculture in Australia are coastal industries of significance culturally, financially and in the provision of food. Both the wild catch and aquaculture industries exploit multiple species, and the interaction between climate change and the seafood sector is complex because of the variability in likely responses of exploited and non-exploited species. The effects of a changing climate will also be felt differently around the country.

Broadly, the threats to each industry (fisheries/aquaculture) are similar, but aquaculture threats are expected to be more manageable (e.g. Richards et al. 2015). This is because aquaculture is typically situated in easily accessible inshore waters, enabling active management of critical habitat qualities (e.g. water quality, habitat structure, temperature). However, aquaculture industries may be subject to greater climatic stress because of their predominantly inshore, shallow water locations. This reduces the buffers afforded more oceanic fisheries as near-shore areas are subject to increased variability in freshwater input and air temperature (Richards et al. 2015). Habitats relevant to coastal fisheries are considered to exhibit intermediate vulnerability to climate change (Figure 1).

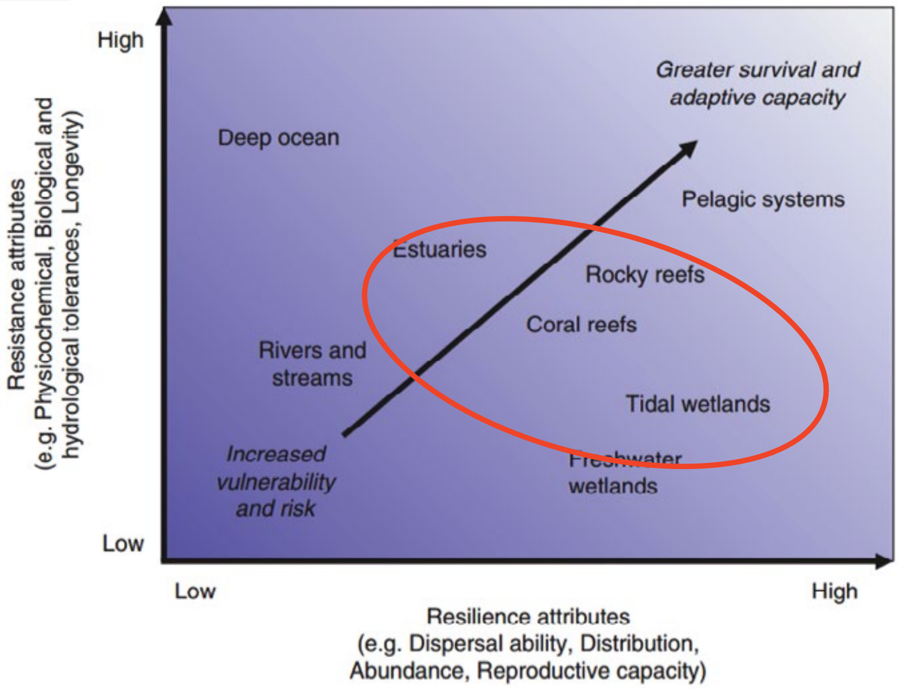

Figure 1: Theoretical vulnerability of aquatic habitats to climate change; habitats supporting coastal fisheries mostly have moderate levels of resistance and resilience attributes, so intermediate vulnerability— see red ellipse. Source: Reproduced from Koehn et al. (2011), with permission from CSIRO Publishing.

Overview of climate impacts

The overall nature of future changes to the climate is predictable (e.g. temperatures will rise), but uncertainty remains in their magnitude. In Australia, climate change is predicted to increase the mean temperature of air and water, cause sea-levels to rise (see Figure 2 for predictions for each state/territory), increase the acidity of the oceans, alter rainfall regimes, drive changes in the timing, intensity, and location of oceanic currents, and increase the frequency and intensity of extreme weather events, including extreme rainfall events, floods and bushfires. Tropical cyclones may become less frequent, but those that do occur are expected to be more intense. Through much of the country there will also be an increase in the number of years spent in drought, with Queensland being the only state where uncertainty remains about the direction of change in future dry periods (Figure 2). Ocean acidity is expected to rise in proportion with atmospheric carbon (CSIRO and Bureau of Meteorology 2015).

Each of these changes is likely to have some effect on important fishery species, however the magnitude of effects remains unclear. Similarly, the direction of change is mostly predictable for individual impacts (e.g. the effect that ocean acidification will have on oysters) but the way these individual impacts will interact makes predicting the net effect problematic. The modelling of these effects on fisheries is a complex task because of the inherent uncertainty associated with each step of assessing potential drivers (Figure 3).

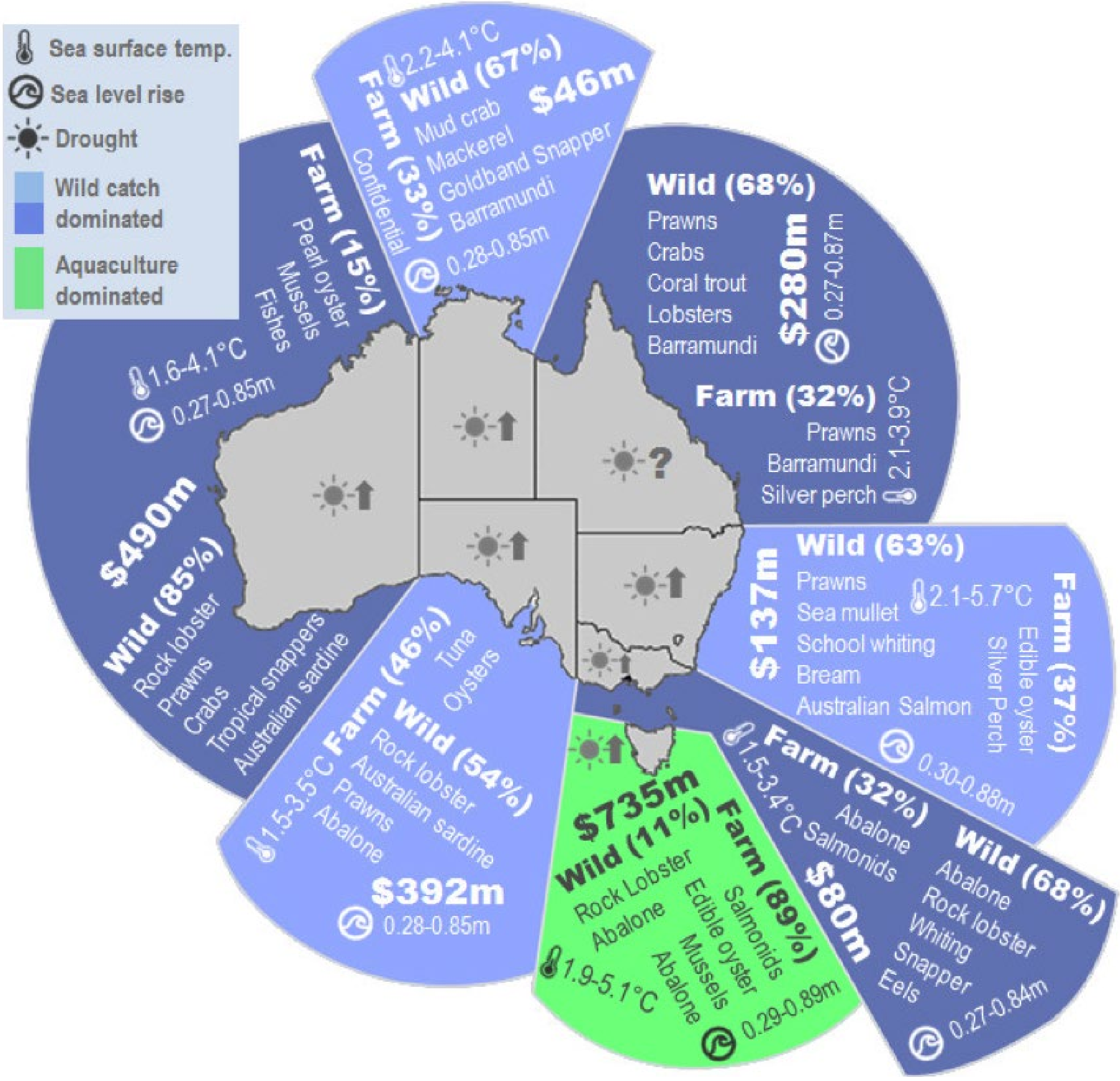

Figure 2: Climate change predictions and key (maximum top 5) wild-catch (Wild) and aquaculture (Farm) coastal fisheries by state/territory. Dollar values represent the economic value in 2013-14. Fisheries are listed in order of economic contribution per state/territory (highest at top). Brackets indicate the percentage of overall fishery yield that each sector contributes to that state/territory. Climate predictions represent change expected by 2090. Source: Fisheries data from Savage and Hobsbawn (2015). Climate predictions from CSIRO and Bureau of Meteorology 2015.

Some broad patterns in species-specific climate responses are possible to infer. Pecl et al. (2014) suggest that fisheries species with high productivity may be less susceptible to long-term change than those with lower productivity. But short-term variability (e.g. marine heatwaves (Pearce and Feng 2013)) may induce a faster (positive or negative) response, especially in highly productive species (Rijnsdorp et al. 2009). The 2011 marine heatwave in Western Australia, for example, was reportedly responsible for large fish kills and a temporary southward distribution shift of tropical fauna (Pearce and Feng 2013). This type of short-term extreme can have devastating long-term impacts, as species respond to breaching of resilience thresholds (e.g. corals in Ainsworth et al. (2016)). A similar, but perhaps more destructive, marine heatwave (consecutive months of record high temperatures) is currently occurring in eastern Australia, resulting in widespread bleaching of corals on the Great Barrier Reef (GBR). This type of widespread coral mortality is likely to trigger deleterious effects on key fisheries species that rely on coral reefs for food and/or habitat.

The impacts of predicted climate changes on fishes and fisheries can be grouped into primary, secondary and tertiary categories (Koehn et al. 2011). Primary threats are those with a direct impact on the target animal's physiology (particularly on growth and reproduction), secondary impacts affect the habitat of target species, and tertiary impacts are those that result from a combination of factors (i.e. interactive effects).

Basing definitions of impacts around the target animal means that some drivers can be primary impacts for one species but secondary for another. This is due to the inherent link between habitat-forming species and species relying on the habitat they provide (Hoegh-Guldberg and Bruno 2010). Oysters, for example, being a habitat-forming species, are likely to be influenced (as a primary impact) by increasing ocean acidity and temperature (e.g. Parker et al. 2009), which may lead to a reduction in overall abundance and/or distribution. Any species that rely on the habitat created by oysters will then be indirectly affected (i.e. as a secondary impact) by these same influencers. Climate change also affects aspects of the fishery supply chain beyond harvesting itself (Fleming et al. 2014; Hobday et al. 2014), although these effects are only now being considered (Plagányi et al. 2014) and are not reviewed in detail here.

Primary impacts

The primary impacts outlined in Table 1 are expected to weaken the individual. They directly affect the organism's ability to optimise its energy budget, and hence draw energy away from core tasks in growth and reproduction. This has a direct effect on the overall fishery of any given species by reducing the size of individuals, but also the population growth rate and ability to recover from losses (e.g. those experienced through fishery harvests). Reductions in fish size can also increase predation risk and hence, the combined primary effects are expected to reduce overall fishery yields (Audzijonyte et al. 2015).

Secondary impacts

Secondary impacts are those that alter habitat structure, the quality of habitat, or the connections between important habitats. These affect species at the population level. They drive changes in the abundance and diversity of communities, and may also affect species distributions. Climate impacts such as sea-level rise, altered rainfall regimes, and increased frequency of extreme weather events can all be considered secondary impacts in this context, and all are likely to affect overall fishery production. These secondary impacts may reduce overall yield from fisheries through a shrinking of the number and size of fishery targets, but also through shifts in the distributions of target species, making harvest efforts more problematic and unpredictable.

It is possible, however, that some target species may benefit from habitat shifts. For example, it is expected that sea surface temperature (SST) increases will increase coral bleaching events, and increasing ocean acidity will reduce corals ability to calcify. This will reduce overall coral cover, and may lead to an increase in macroalgal cover in its place (Bell et al. 2013). Fishery species that benefit from algal rich habitats may be able to exploit this change and thrive, while those that rely heavily on coral habitat will be likely to suffer. Alternatively, species may be forced into distributional changes (Pecl et al. 2014) which benefit some jurisdictions to the detriment of others. For example, the eastern rock lobster may undergo a southward distribution shift, enabling southern fishers to exploit this species for the first time (Pecl et al. 2009). However, the benefit of this new resource is unlikely to compensate for losses elsewhere. See *Case study 3: Rock lobster fisheries* for further information.

Tertiary impacts

Tertiary impacts are not well understood. The complexity of the interactions between multiple climate drivers makes the overall effect difficult to predict. The current use of end-to-end models goes some way to understanding the interaction between these effects (e.g. Plagányi et al. 2011). These end-to-end models have been implemented in fisheries management through use of the Atlantis (in SE Australia) and InVitro (in NW Australia) models (Fulton 2011; Fulton et al. 2007; Gray et al. 2006). However, variability at every stage of the process (i.e. from data collection to input of model parameters (see Figure 3)) means that a clear understanding of future impacts is still difficult to obtain. Therefore, further research and modelling are required to improve predictive ability.

Some assessment has been conducted on the likely effect of climate changes on key fisheries species within Australia. For example, Pecl et al. (2014) developed a rapid assessment model to assist in management efforts. This was achieved partly through assessment of the relative susceptibility of key species to individual climate drivers (Table 2). This assessment suggests a relatively good understanding around the potential effects of temperature increases, but also points to a paucity of knowledge around most other drivers and their interactions.

Table 1: Expected primary, secondary, and tertiary impacts on Australian fish and fisheries. Sources: Findlay et al. (2009) for acidification, Leung and Bates (2013) for disease, and Koehn et al. (2011) for other topics.

Impact category	Driver for change in fishery	Contributing climate effect	Effect on fishery organisms
Primary	Direct effect	Increased sea temperature	• Diversion of energy away from growth/ reproduction to maintenance • Changes to spawning period and duration • Smaller eggs and hatch size • Reduced number and quality of offspring • Altered swimming performance • May have positive effect in some species through accelerated development
		Ocean acidification	• Weakening of calcareous exoskeletons • Acidosis in non-calcifying organisms, especially early life stages
		Salinity changes (primarily in estuarine environments)	• Increased stress through changes to metabolism and oxygen consumption • Changes to spatial distribution due to altered river flows and thus coastal salinity
		Altered current regimes & timing of seasonal upwelling	• Altered migration timing and routes • Altered food presence • Altered reproduction and larval dispersal
		Increased prevalence and distribution of diseases	• Increased mortality
Secondary	Changes to habitat structure or quality	Sea-level rise	• Reduction and/or redistribution of habitat- forming organisms (e.g. seagrasses, corals). • Associated reduction/redistribution in suitable habitat for fishery species • Increased seawater flow into estuaries • Loss of juvenile habitat for commercially important fish species
		Altered rainfall regimes	• Salinity changes affect habitat-forming organisms (as above) • Reduced flows diminish connectivity between estuary and river and among habitats
		Increased sea temperature	• Physiological stress on habitat-forming species
		Extreme weather	• Destruction of habitat • Increase pulse flows of land borne pollutants
Tertiary	Combination of drivers: poorly defined, difficult to predict	EXAMPLE: Climate driven changes to species distributions (native and invasive)	• Increased resource competition among fishery species • Potential loss of resources • **See case studies for examples**

Table 2: The expected susceptibility of fishery species to key climate drivers.

Relative impact: high (***), medium (**), and low (*); '?' represents uncertainty; blanks represent a total lack of understanding of the relationship between a species and driver. Biological drivers suggest a reliance between the target species and the abundance/distribution of other listed organisms. Source: Pecl et al. 2014.

Species or species group	Temperature	Salinity	Upwelling	Winds & currents	pH	Nutrients/ plankton	Freshwater flows	Biological
Abalone	***				***?			*** sea urchins & pathogens
Australian salmon	*			***	*?			
Black bream	*	*			*?		***	*yellowfin bream, HABs
Blue grenadier	**?			*	*?			
Blue swimmer crab	***	***			*?			
Commercial scallops	**?				***?			
Eastern king prawn	**	*?		**	*?		**	
Flatheads	*	*?		*	*?	*	*	* seagrass
Gummy shark	*?				*?		*?	
King George whiting	**			**	*?	**?		** seagrass
School prawn		*?			*?		***	
Small pelagics	***		***	***	*?	***		**jack mackerel, krill
Snapper	**			**	*?			
Southern bluefin tuna	**		***	*	*?			** small pelagics
Southern calamari	***	*			*?			* seagrass & macroalgae
Southern garfish					*?			*** seagrass
Southern rock lobster	***			**?	*?			*** sea urchins, macroalgae, octopus, Eastern rock lobster
Spanner crabs	**			*	*?			
Striped marlin	**			**	*?			
Tunas, other	**			***	*?			
Western king prawns	***	*	***	*	*?			
Yellowtail kingfish	**			**	*?			

Sectorial breakdown of expected impacts on key fisheries

The target species will define the overall effect that climate change will have on Australian fisheries, with some species being more susceptible to particular changes than others. For example, species which already exist at the boundaries of their thermal tolerances (e.g. the Tasmanian salmon aquaculture sector) may be more susceptible to rising temperatures than those with a more cosmopolitan distribution. Thus, it is important to know which species are involved in Australian fisheries, and where they are primarily harvested, in order to predict potential effects on the fisheries overall.

Overview of fishery value to Australian economy

By weight, fin fish dominate total fishery production (Table 3, salmonids, sardines, tuna). However, in economic value, calcifying (non-fish) products account for a large proportion (Table 3, rock lobster, prawns, and abalone (Savage and Hobsbawn 2015)). This is noteworthy because the nature of climate change impacts on calcifying versus non-calcifying species is different, especially with regard to the effects of ocean acidification.

Table 3: Top five fishery products in Australia (combined wild catch & aquaculture, 2013-14) as defined by weight and by economic value. Source: Savage and Hobsbawn 2015.

By weight	'000 tonnes	By value	$ millions
Salmonids	41.8	Rock lobsters	586
Sardines	35.9	Salmonids	543
Prawns	24.9	Prawns	337
Oysters	11.4	Abalone	165
Tuna	10.7	Tuna	147

Wild catch fisheries

There are numerous wild catch fisheries in Australia's coastal waters, with calcifying species (prawns, crabs, lobsters, and oysters) topping the production value in every management area. In monetary terms, Commonwealth jurisdiction fisheries along with those managed by Western Australia and South Australia account for 64% of wild catch fishery production value (Savage and Hobsbawn 2015).

Aquaculture

Salmonids (e.g. salmon and trout) account for more than 50% of the overall economic return in Australian aquaculture, with tuna, oysters, and prawns accounting for much of the remaining economic value. Tasmania and South Australia account for 74% of Australia's aquaculture production value (Savage and Hobsbawn 2015).

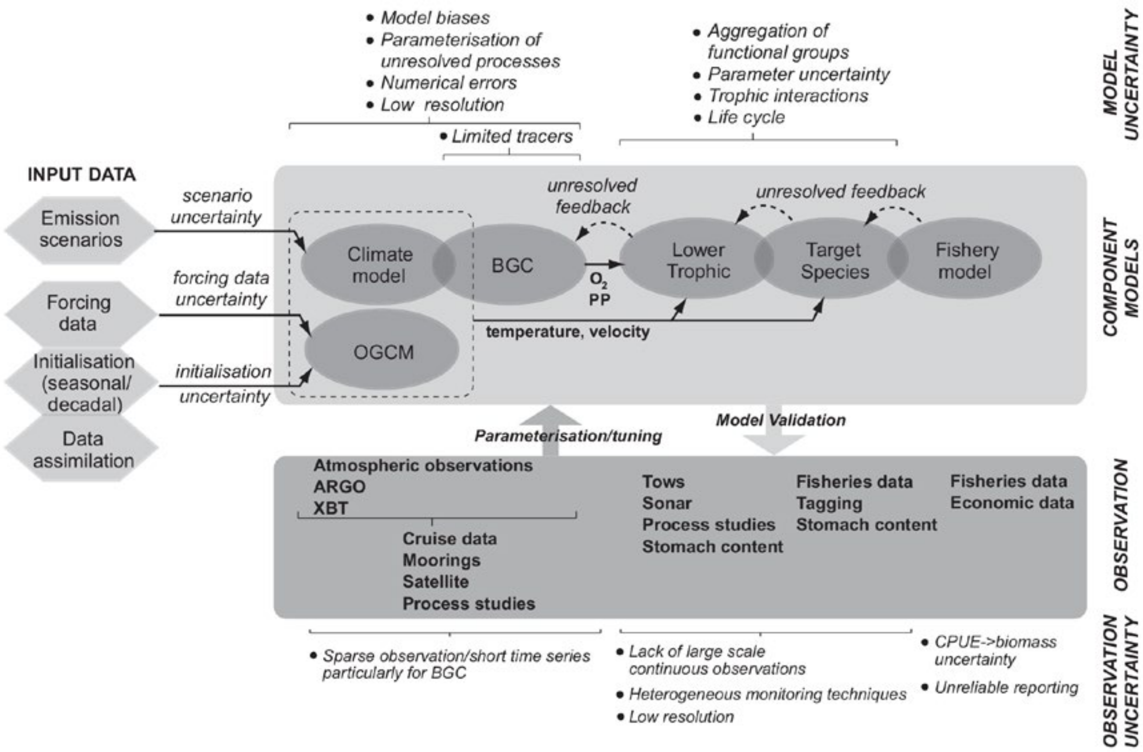

Figure 3: Schematic diagram of components potentially included in a physical-biogeochemical-ecosystem modelling framework of the impacts of climate change on fisheries. Uncertainties associated with each of the components of the framework are in italics. OGCM: ocean general circulation model; BGC: biogeochemistry; PP: primary production; ARGO: array for real-time geostrophic oceanography; XBT: expendable bathythermograph; CPUE: catch per unit effort. Source: Evans et al. 2015.

Species by state/territory

Calcifying organisms (e.g. prawns, oysters, abalone, crabs, lobsters) dominate catch value in almost every state, topping both wild catch and aquaculture products in most cases (Tasmanian and South Australian aquaculture industries being the exceptions) (Figure 2). Within aquaculture, a qualitative risk assessment of key products found that oysters are the most at risk of the effects of climate change due to their susceptibility to changes in temperature, salinity, acidity and disease outbreaks (Doubleday et al. 2013); see *Case study 4: Oyster aquaculture* for more information. These organisms are generally harvested near-shore and, as such, are potentially more susceptible to climate change impacts than offshore fisheries. Calcifying organisms are expected to be most affected by increasing ocean acidity because of its direct effect on their exoskeletons. This has the potential to cause thinning of shells, which reduces predator defence, and/or requires the animals to divert energy away from growth and reproduction in order to maintain their calcareous structures. Temperature increases are likely to have similar effects in reducing growth and reproduction in these species.

Overall, it can be expected that fisheries for calcifying organisms in Australia may experience reductions in the overall size and quality of catches, along with a reduced ability for stocks to replenish following harvests. Many of these species, as filter feeders, are also vulnerable to disease: Pacific Oyster Mortality Syndrome (POMS) for oysters, withering syndrome for abalone, harmful algal blooms for oysters and mussels.

Non-calcifying organisms (e.g. fin-fishes) are likely to experience similar stressors on growth and reproduction due to increasing ocean temperatures, with sea-level rise also contributing to changes to available habitat. This is likely to reduce catch sizes, and also make locating populations of wild catch fishes more difficult as the tropicalisation of temperate waters disperses animals beyond their current ranges. These changes in distribution may affect the ability of individual species to reproduce and replenish in response to harvest losses. Additionally, they may also affect the ability of fishers to find or access fish stocks for harvest; for example, if populations move into conservation areas or beyond territorial jurisdictions (e.g. McIlgorm et al. 2010). It has also been noted in eastern Australia that, along with distributional shifts, species distributions may also contract because the rate of change at the leading edge of the range shift can be slower than that at the trailing edge for many commercially important fishes (Robinson et al. 2015). It is possible that any increased difficulty in locating animals for harvest may be counteracted by technological advances. The use of satellites, for example, to rapidly learn the location of warm versus cold waters, is already providing fishers with vital knowledge about where their targets might be. Seasonal forecasting is also being used to reduce risk for managers and fishers in several regions of Australia (Hobday et al. 2016).

Case studies

Understanding of the effects of climate change on Australian coastal fisheries, particularly of multiple stressors, is still far from complete. Therefore the following case studies aim to highlight the potential effects that a changing climate may have on individual fisheries.

Case study 1: Prawn fisheries

Prawn fisheries are important contributors to the economy in several Australian jurisdictions. Prawns top the list of wild catch in New South Wales and Queensland, as well as for aquaculture in Queensland. While prawn aquaculture is important, this case study focusses on Queensland's wild catch prawn fisheries, and the potential impacts that climate change may have on fishery returns.

In Queensland, climate change is expected to increase SST by up to 3.9°C by 2090, with concomitant sea-level rise of up to 0.87 m (Figure 2). From these specific regional predictions, along with ocean acidification, it can be expected that there will be increased physical stress directly on the prawns, and on their habitats through more intense cyclone activity and flooding events.

Key drivers

This section summarises the climate variables likely to have the *most* impact on prawn fisheries, with a focus on those in Queensland. It is not intended to be a comprehensive review of all potential impacts.

Ocean acidity

The effect of ocean acidification on calcifying animals is one of the better understood primary impacts (Narita et al. 2012). Changes in ocean acidity alone can reduce growth rates and reproductive output in calcifying organisms. This change can also increase susceptibility to predation through weakening of protective exoskeletons, along with affecting an animal's ability to maintain its acid-base equillibria.

Prawns, however, may be more resilient to the effects of ocean acidity than other calcifiers through regulation of the ions involved with calcification (Richards et al. 2015). This allows them to maintain, or even increase the rate at which they calcify exoskeletons under elevated ocean acidity (Richards et al. 2015). It is also thought that many prawn species are able to compensate for acid changes and increase their ability to maintain acid-base equilibria (Richards et al. 2015). These compensatory mechanisms, however, are likely to draw heavily on the overall energy budget of individual prawns, leaving less energy available for growth and reproduction (Richards et al. 2015). So, despite higher tolerance for ocean acidity than other calcifiers, it would still be likely to cause a considerable reduction in fishery returns.

The projected changes in ocean acidity closely match those predicted for the rest of the world, with only subtle regional and temporal differences that are not yet well understood (Hobday and Lough 2011; Lenton et al. 2015). In Queensland waters, ocean pH is lower (i.e. more acidic) than in much of the rest of the country, and will continue to decline as atmospheric CO_2 increases (Hobday and Lough 2011; Lenton et al. 2015).

Sea temperature rise

Increasing water temperature is likely to induce increased physiological stress on prawns, which is ultimately expected to also reduce growth rates and reproductive outputs. It is possible that it may also trigger range shifts in some species. However, for range shifts to be possible, there must also be suitable habitat for the animals to occupy, which may be problematic if key habitat-forming species (e.g. seagrasses for tiger prawns, and mangroves for banana prawns) are not present and do not colonise new areas quickly enough.

Sea-level rise

Sea-level rise is considered a secondary impact because it is likely to affect the availability and quality of habitat (Koehn et al. 2011). The effect of this on adult prawns may be negligible given that all Queensland species are generally found in depths >10m, and on sand or mud substrates (see Table 1 in Richards et al. 2015). However, juveniles of all species use shallow waters (often seagrass/algal beds or mangroves) as a nursery habitat (see Table 1 in Richards et al. 2015). Rising sea-levels, along with coastal squeeze induced by urbanisation and development, are expected to substantially reduce the extent and/or quality of these shallow-water habitats, in turn negatively affecting the viability of the fishery.

Interaction between effects

The individual effects described above are expected to contribute to ongoing declines in the viability of the target species, but only when the interactions between all possible effects are considered will there be a clear picture of the future of prawn fisheries in Queensland. But, here we present the expected direction of change for key climate impacts in an effort to address the interaction between impacts and predict the net effect on the fishery (Figure 4). Ultimately, some changes have the potential to induce positive effects on habitat availability or growth/reproduction, but the net effect across all categories is expected to result in a negative change in yields.

	Growth & reproduction	Habitat availability	Net change in fishery returns
Ocean acidification	↓	↕	↓
Increased SST	↓	↕	↓
Sea-level rise	↕	↓	↓
Increased cyclones	↕	↓	↓
Increased flooding	↓	↓	↓
Net change	↓	↓	↓

Figure 4: Summary of the direction of likely effects of climate factors on Queensland prawn fisheries. RED downward arrows represent a negative effect on overall yields. Green double headed arrows represent uncertainty around the direction of effect on yield. Source: Developed by the Author.

Case study 2: Salmon aquaculture

The salmonid aquaculture industry in Australia occurs predominantly in Tasmania. This industry is very valuable to the Australian economy ($543 million in 2013-14, Figure 2), but is also likely to be threatened under all future climate change scenarios. Rising sea temperatures are of particular concern to this industry. Salmon farming occurs at the upper limit of species thermal tolerance, and increases in ocean temperature of 2-3°C may render the industry unviable unless alternative locations (i.e. deeper and/or further offshore) are utilised (Hobday et al. 2008).

More than a decade ago, increases in summer temperatures were considered the probable cause of increased fish mortality in the industry (Pittock 2003), which suggests that future increases are likely to result in substantial decreases in overall yield. Further expected effects from increased temperatures are delayed ovulation and reduced quality of offspring in Atlantic salmon (Pankhurst and King 2010).

The production of salmon in Australia is carefully managed, and several adaptive strategies have been employed to combat changes in climate. Selective breeding, for example, targets individuals that grow and reproduce more efficiently at higher temperatures. Seasonal forecasting is also used as an adaptive management strategy in the Australia salmon aquaculture industry (Spillman and Hobday 2014).

While temperature increases are the most obvious threat, there appears to be a lack of understanding of how other climate variables may affect the salmonid industry in Australia. It is likely that other changes may affect yields, for example through more extreme weather events that may increase run-off from the land. However, these other influences appear to be unexplored and may be of low significance compared to the effect of increasing temperatures.

Case study 3: Rock lobster fisheries

Rock lobsters are important, high value products in many Australian states. They are the highest value wild catch product in Western Australia, South Australia, and Tasmania, and second highest in Victoria (Figure 2). The southern (*Jasus edwardsii*) and western (*Panulirus cygnus*) rock lobsters account for the bulk of catches in these states. Like prawns, rock lobsters are a calcifying crustacean, but they are likely to be more vulnerable to a somewhat different set of climate stressors due to differences in habitat usage and life-history traits.

Both primary and secondary stressors are expected to alter returns in lobster fisheries over the coming century. Hence, it is likely that tertiary (interactive) effects will also become important although, again, these are less well understood. Pecl et al. (2009) list warming waters as the primary driver of change for the Tasmanian rock lobster fishery. Other key drivers of change expected in this fishery are rising sea levels and ocean acidification (Pecl et al. 2009).

Sea temperature rise

Warming ocean temperatures are expected to induce numerous primary and secondary effects on lobster fisheries throughout Australia. This is because, as previously discussed, warming waters can directly affect the physiology of an animal, and hence affect capacity for growth and reproduction. Warming waters may actually increase growth rates and the frequency of moulting events for lobsters but, given the parabolic nature of this relationship, near the upper end of thermal tolerances it can also have the opposite effect (Green et al. 2014).

Increasing sea temperatures can also have wider secondary impacts by inducing changes in the strength of ocean currents and shifting the distribution of species. These two factors in particular are expected to have substantial impacts on rock lobster fisheries throughout Australia. A strengthening of the Leeuwin Current (which runs southward along the Western Australian coastline and then eastward toward Tasmania) has already been linked to altered migration patterns, and hence distributional shifts, in western rock lobsters (de Lestang and Caputi 2015). This has been shown to reduce catches within the northern areas of the Western Australian rock lobster fishery. However, climate models suggest that this current may weaken by 15-20% by 2060 (Caputi et al. 2015).

Warming waters, and associated altered current strengths, have also been linked to distribution shifts of other species, which can then in turn affect catches in rock lobster fisheries. This can occur through a function of competitive stress or changes in predator-prey relationships (Pecl et al. 2009). For example, it has been suggested that the eastern rock lobster (*Jasus verreauxi*) may undergo a range shift southward, putting it into the natural range of the southern rock lobster (Pecl et al. 2009). This may create a competitive stress, but may also open opportunities for fishers to exploit the newly-arrived species. Shifts in sea urchin distributions are also expected to affect lobster fisheries (e.g. Ling et al. 2009b). Sea urchins can change habitat structure dramatically (Ling et al. 2009a), and are known to reduce the quality of lobster habitat. However, they are also a known prey item, especially for large lobsters (Ling et al. 2009a; Pecl et al. 2009).

Other effects expected from increasing sea temperatures include changes to catchability (with higher catchability at warmer temperatures), natural mortality rates, and altered settlement to benthic habitats in both time and space (Caputi et al. 2009; Green et al. 2014).

Ocean acidity

Pecl et al. (2009) highlight a lack of understanding around the direct effects of ocean acidification on Australian lobster species, and there appears to be no direct study of this relationship. This was also cited as a knowledge gap by Caputi et al. (2015). However, inferring from investigations on other lobster species, and on other crustaceans, it can be expected that ocean acidity will have some effect. In this case, the effect is expected to be similar to that for prawns described above. That is, increased acidity may negatively affect growth rates and reproductive output, but the effect on calcification itself may be negligible, at least in the short-medium term (Whiteley 2011). Overall, increases in ocean acidity are expected to reduce the size of individuals and populations and hence reduce overall fishery returns.

Case study 4: Oyster aquaculture

It has been projected that ocean acidification alone will result in losses of up to US$141 billion in global mollusc production by the end of the century; this from an industry valued at ~US$150 billion in 2011 (Narita et al. 2012). Oysters comprise a considerable proportion of this, and are also important contributors to Australian seafood production. Overall, oyster production currently represents approximately $190 million value to the Australian economy annually, with pearl oyster farming accounting for ~$100 million, and edible oyster the other $90 million (Savage and Hobsbawn 2015). As mentioned, they are particularly susceptible to increasing ocean acidity, but also a host of other climate related changes. The key primary impacts on oysters include increases in ocean acidity and temperature, altered rainfall patterns, and disease (Doubleday et al. 2013).

Three main species of oyster are farmed in Australia: the introduced Pacific oyster (*Crassostrea gigas*); the native Sydney rock oyster (*Saccostrea glomerata*, formerly *S. commercialis*); and the native angasi (*Ostrea angasi*) (Nell 1993).

Ocean acidity and sea temperature rise

The effects of increasing ocean acidity and sea temperature rise (as individual primary stressors) on oysters are expected to be similar to those of other calcifying organisms (see prawns and rock lobsters). However, some studies have investigated the tertiary (or interactive) effects of multiple stressors on oysters. Here we explore the findings of Parker et al. (2009) on the interactive effects of increasing temperature and acidity, and later the interactive effects of temperature and pollutants (see Lannig et al. (2006) reference in Altered Rainfall section).

Parker et al. (2009) investigated the effect of increased temperature and acidity on fertilization and embryonic development of Sydney rock oysters under various climate scenarios possible by 2100. In general, fertilisation decreases as acidity increases, and as temperature varies away from an optimal 26°C (in either direction). At high temperatures and high acidity, growth was impaired and mortality increased. In the highest treatments (30°C with low pH (pCO_2>750ppm)), there was no larval development at all (Parker et al. 2009). This study suggests that the combined effects of increasing sea temperatures and acidity represent critical threats to oyster production in Australia, especially if worst-case scenarios occur.

Altered rainfall

Oysters are tolerant of a wide range of salinities, but given their habitat is generally within estuaries, there is potential for them to be exposed to salinities at which they are vulnerable. Pacific oysters are particularly susceptible to increases in predatory flatworms (Doubleday et al. 2013), which can be triggered by high salinity induced by drought (O'Connor and Newman 2001). Rainfall also affects catchment inputs into estuaries, potentially affecting oyster growth, reproduction, and survival. Land uses in catchments will dictate the type and abundance of these inputs, but higher rainfall will potentially increase pulse inputs.

Sydney rock oysters can survive in salinities from 15 to 55‰, but optimum growth occurs in a narrower range (25 to 35‰ for adults) (Nell and Gibbs 1986; Nell 1993). Continuous exposure to salinities outside the optimal range can therefore reduce yields in oyster farms. Changes to rainfall regimes may trigger this shift in either direction, with extended drought potentially inducing hypersaline conditions in some estuaries, while increased and persistent rainfall may create lower salinities.

Increased pollutant and nutrient input (from increased rainfall) also has the potential to alter growth, abundance and distribution of oysters, and hence may cause a change in yield. However, the relationship between pollutants and oyster production is confounded by interacting effects. For example, the growth rate of Sydney rock oysters is higher in developed areas (with associated higher concentrations of anthropogenic nutrients and pollutants), but mortality is also higher in these areas (Paterson et al. 2003). Pollutant and nutrient inputs have also been directly related to crashes in aquaculture production through "acid soil and anoxic runoff, poor sewage management systems, and harmful algae blooms" (Creighton 2013, pg. 6).

While anthropogenic inputs can have direct effects on oyster growth, they also reduce stress tolerance, including to increasing temperatures (Lannig et al. 2006). The interactive effects (tertiary impacts) on growth, reproduction and resistance to disease might further compound losses in yield. Increases in waterway pollutants, which are then assimilated into oyster tissues, also represent a direct health risk to consumers. Sydney rock oysters from the Hawkesbury River estuary (New South Wales) were previously found with some metals (e.g. selenium) in concentrations higher than the maximum permitted by the National Food Authority (1992) (Hardiman and Pearson 1995).

Disease

Disease has a major impact on oyster aquaculture. QX disease has triggered crashes in Sydney rock oyster populations , while the Pacific oyster (that is resistant to this disease) is susceptible to Pacific Oyster Mortality Syndrome (Creighton 2013). Both the prevalence of diseases, and oysters' ability to resist them, may be affected by a changing climate. For example, ocean warming has been attributed to a range expansion in oyster diseases (Harvell et al. 2002). Temperature changes, especially in combination with increased pollutant inputs, are likely to reduce stress tolerance in oysters, and this may render them less resistant to disease. Oysters and other shellfish can also directly transfer dangerous diseases to humans (Rippey 1994), representing a further human health risk.

The combination of all of these impacts is likely to have negative effects on oyster aquaculture yields.

References

Ainsworth, T. D., and Coauthors, 2016: Climate change disables coral bleaching protection on the Great Barrier Reef. *Science*, **352,** 338-342.

Audzijonyte, A., E. A. Fulton, and A. Kuparinen, 2015: The impacts of fish body size changes on stock recovery: a case study using an Australian marine ecosystem model. *ICES Journal of Marine Science: Journal du Conseil*, **72,** 782-792.

Bell, J. D., and Coauthors, 2013: Mixed responses of tropical Pacific fisheries and aquaculture to climate change. *Nature Climate Change*, **3,** 591-599.

Caputi, N., R. Melville-Smith, S. de Lestang, A. Pearce, and M. Feng, 2009: The effect of climate change on the western rock lobster (*Panulirus cygnus*) fishery of Western Australia. *Canadian Journal of Fisheries and Aquatic Sciences*, **67,** 85-96.

Caputi, N., and Coauthors, 2015: Management implications of climate change effect on fisheries in Western Australia, Part 1: Environmental change and risk assessment. *FRDC Project No 2010/535*. Accessed 8 February 2018. [Available online at http://www.fish.wa.gov.au/Documents/research_reports/frr260.pdf].

Creighton, C., 2013: Revitalising Australia's estuaries. *Final report to the Fisheries Research and Development Corporation, Project*, **36**.

CSIRO and Bureau of Meteorology, 2015: Climate Change in Australia. Accessed 19 May 2016. [Available online at http://www.climatechangeinaustralia.gov.au/en/].

de Lestang, S., and N. Caputi, 2015: Climate variability affecting the contranatant migration of *Panulirus cygnus*, the western rock lobster. *Marine Biology*, **162,** 1889-1900.

Doubleday, Z. A., and Coauthors, 2013: Assessing the risk of climate change to aquaculture: a case study from south-east Australia. *Aquaculture Environment Interactions*, **3,** 163-175.

Evans, K., J. N. Brown, A. Sen Gupta, S. J. Nicol, S. Hoyle, R. Matear, and H. Arrizabalaga, 2015: When 1+1 can be >2: Uncertainties compound when simulating climate, fisheries and marine ecosystems. *Deep Sea Research Part II: Topical Studies in Oceanography*, **113,** 312-322.

Findlay, H., H. Wood, M. Kendall, J. Spicer, R. Twitchett, and S. Widdicombe, 2009: Calcification, a physiological process to be considered in the context of the whole organism. *Biogeosciences Discussions*, **6,** 2267-2284.

Fleming, A., A. Hobday, A. Farmery, E. Van Putten, G. Pecl, B. Green, and L. Lim-Camacho, 2014: Climate change risks and adaptation options across Australian seafood supply chains–A preliminary assessment. *Climate Risk Management*, **1,** 39-50.

Fulton, E., 2011: Interesting times: winners, losers, and system shifts under climate change around Australia. *ICES Journal of Marine Science: Journal du Conseil*, **68,** 1329-1342.

Fulton, E., A. Smith, and D. Smith, 2007: Alternative Management Strategies for Southeast Australian Commonwealth Fisheries: Stage 2: Quantitative Management Strategy Evaluation. Commonwealth Scientific and Industrial Research Organisation (CSIRO). Accessed 19 May 2016. [Available online at http://atlantis.cmar.csiro.au/www/en/atlantis/mainColumnParagraphs/02/text_files/file/AMS_Final_Report_v6.pdf].

Gray, R., E. Fulton, L. Little, and R. Scott, 2006: Operating model specification within an agent based framework. North West Shelf Joint Environmental Management Study Technical Report, vol. 16. CSIRO, Hobart, Tasmania.

Green, B. S., C. Gardner, J. D. Hochmuth, and A. Linnane, 2014: Environmental effects on fished lobsters and crabs. *Reviews in Fish Biology and Fisheries*, **24,** 613-638.

Hardiman, S., and B. Pearson, 1995: Heavy metals, TBT and DDT in the Sydney rock oyster (*Saccostrea commercialis*) sampled from the Hawkesbury River estuary, NSW, Australia. *Marine Pollution Bulletin*, **30,** 563-567.

Harvell, C. D., C. E. Mitchell, J. R. Ward, S. Altizer, A. P. Dobson, R. S. Ostfeld, and M. D. Samuel, 2002: Climate warming and disease risks for terrestrial and marine biota. *Science*, **296,** 2158-2162.

Hobday, A., E. Poloczanska, and R. Matear (Eds.)., 2008: *Implications of climate change for Australian fisheries and aquaculture: a preliminary assessment.* Department of Climate Change, Commonwealth of Australia, Canberra, Australia. Accessed 8 February 2018. [Available online at http://fish.gov.au/reports/Documents/hobday_etal_2007_Implications_of_climate_change_for_fisheries_20080801_PDF.pdf].

Hobday, A. J., and J. M. Lough, 2011: Projected climate change in Australian marine and freshwater environments. *Marine and Freshwater Research*, **62,** 1000-1014.

Hobday, A. J., C. M. Spillman, J. Paige Eveson, and J. R. Hartog, 2016: Seasonal forecasting for decision support in marine fisheries and aquaculture. *Fisheries Oceanography*, **25,** 45-56.

Hobday, A. J., and Coauthors, 2014: 16 Growth opportunities for marine fisheries and aquaculture industries in a changing climate. *Applied Studies in Climate Adaptation*, 139.

Hoegh-Guldberg, O., and J. F. Bruno, 2010: The impact of climate change on the world's marine ecosystems. *Science*, **328,** 1523-1528.

Koehn, J. D., A. J. Hobday, M. S. Pratchett, and B. M. Gillanders, 2011: Climate change and Australian marine and freshwater environments, fishes and fisheries: synthesis and options for adaptation. *Marine and Freshwater Research*, **62,** 1148-1164.

Lannig, G., J. F. Flores, and I. M. Sokolova, 2006: Temperature-dependent stress response in oysters, *Crassostrea virginica*: pollution reduces temperature tolerance in oysters. *Aquatic Toxicology*, **79,** 278-287.

Lenton, A., K. L. McInnes, and J. G. O'Grady, 2015: Marine Projections of Warming and Ocean Acidification in the Australasian Region. *Australian Meteorological and Oceanographic Journal*, **65** (1).

Leung, T. L., and A. E. Bates, 2013: More rapid and severe disease outbreaks for aquaculture at the tropics: implications for food security. *Journal of applied ecology*, **50,** 215-222.

Ling, S., C. Johnson, S. Frusher, and K. Ridgway, 2009a: Overfishing reduces resilience of kelp beds to climate-driven catastrophic phase shift. *PNAS*, **106,** 22341-22345.

Ling, S., C. Johnson, K. Ridgway, A. Hobday, and M. Haddon, 2009b: Climate-driven range extension of a sea urchin: inferring future trends by analysis of recent population dynamics. *Global Change Biology*, **15,** 719-731.

McIlgorm, A., S. Hanna, G. Knapp, P. Le Floc'H, F. Millerd, and M. Pan, 2010: How will climate change alter fishery governance? Insights from seven international case studies. *Marine Policy*, **34,** 170-177.

Narita, D., K. Rehdanz, and R. S. Tol, 2012: Economic costs of ocean acidification: a look into the impacts on global shellfish production. *Climatic Change*, **113,** 1049-1063.

Nell, J., and P. Gibbs, 1986: Salinity tolerance and absorption of L-methionine by some Australian bivalve molluscs. *Marine and Freshwater Research*, **37,** 721-727.

Nell, J. A., 1993: Farming the Sydney rock oyster (*Saccostrea commercialis*) in Australia. *Reviews in Fisheries Science*, **1**, 97-120.

O'Connor, W., and L. Newman, 2001: Halotolerance of the oyster predator, Imogine mcgrathi, a stylochid flatworm from Port Stephens, New South Wales, Australia. *Hydrobiologia*, **459**, 157-163.

Pankhurst, N. W., and H. King, 2010: Temperature and salmonid reproduction: implications for aquaculture. *Journal of Fish Biology*, **76**, 69-85.

Parker, L. M., P. M. Ross, and W. A. O'Connor, 2009: The effect of ocean acidification and temperature on the fertilization and embryonic development of the Sydney rock oyster *Saccostrea glomerata* (Gould 1850). *Global Change Biology*, **15**, 2123-2136.

Paterson, K. J., M. J. Schreider, and K. D. Zimmerman, 2003: Anthropogenic effects on seston quality and quantity and the growth and survival of Sydney rock oyster (*Saccostrea glomerata*) in two estuaries in NSW, Australia. *Aquaculture*, **221**, 407-426.

Pearce, A. F., and M. Feng, 2013: The rise and fall of the "marine heat wave" off Western Australia during the summer of 2010/2011. *Journal of Marine Systems*, **111**, 139-156.

Pecl, G., and Coauthors, 2009: The east coast Tasmanian rock lobster fishery–vulnerability to climate change impacts and adaptation response options. Report to the Department of Climate Change, Australia. Accessed 19 May 2016. [Available online at http://www.environment.gov.au/climate-change/adaptation/publications/east-coast-tasmanian-rock-lobster-fishery-vulnerability-climate-change-impacts-and].

Pecl, G. T., and Coauthors, 2014: Rapid assessment of fisheries species sensitivity to climate change. *Climatic Change*, **127**, 505-520.

Pittock, A. B., 2003: *Climate change: an Australian guide to the science and potential impacts.* Australian Greenhouse Office, Canberra. Accessed 19 May 2016. [Available online at http://www.ccma.vic.gov.au/soilhealth/climate_change_literature_review/documents/organisations/ago/science-guide.pdf].

Plagányi, É. E., and Coauthors, 2011: Modelling climate-change effects on Australian and Pacific aquatic ecosystems: a review of analytical tools and management implications. *Marine and Freshwater Research*, **62**, 1132-1147.

Plagányi, É. E., and Coauthors, 2014: A quantitative metric to identify critical elements within seafood supply networks. *PloS one*, **9**, e91833.

Richards, R. G., A. T. Davidson, J.-O. Meynecke, K. Beattie, V. Hernaman, T. Lynam, and I. E. van Putten, 2015: Effects and mitigations of ocean acidification on wild and aquaculture scallop and prawn fisheries in Queensland, Australia. *Fisheries Research*, **161**, 42-56.

Rijnsdorp, A. D., M. A. Peck, G. H. Engelhard, C. Möllmann, and J. K. Pinnegar, 2009: Resolving the effect of climate change on fish populations. *ICES Journal of Marine Science: Journal du Conseil*, fsp056.

Rippey, S. R., 1994: Infectious diseases associated with molluscan shellfish consumption. *Clinical Microbiology Reviews*, **7**, 419-425.

Robinson, L., A. Hobday, H. Possingham, and A. Richardson, 2015: Trailing edges projected to move faster than leading edges for large pelagic fish habitats under climate change. *Deep Sea Research Part II: Topical Studies in Oceanography*, **113**, 225-234.

Savage, J., and P. Hobsbawn, 2015: Australian fisheries and aquaculture statistics 2014. ABARES, Ed., Fisheries Research and Development Corporation.

Spillman, C. M., and A. J. Hobday, 2014: Dynamical seasonal ocean forecasts to aid salmon farm management in a climate hotspot. *Climate Risk Management*, **1**, 25-38.

Whiteley, N., 2011: Physiological and ecological responses of crustaceans to ocean acidification. *Mar Ecol Prog Ser*, **430**, 257-271.

This Impact Sheet was prepared by Ryan Pearson and Rod Connolly from Griffith University. Please cite as:

Pearson, R., and R. Connolly, 2016: Climate change impacts on coastal fisheries and aquaculture. CoastAdapt Impact Sheet 7, National Climate Change Adaptation Research Facility, Gold Coast.