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CSIRO Submission 16/564

Inquiry into the impacts of climate change on marine fisheries and biodiversity

Senate Standing References Committee on Environment and Communications

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Table of Contents

Executive Summary

This submission draws on CSIRO's extensive experience and international recognition in many facets of fisheries and climate research. In addressing these Terms of Reference, responses have been limited to matters with a technical and research focus. Management issues where CSIRO has had direct engagement with state and Commonwealth fisheries management systems, or with industry partners are commented upon as appropriate. CSIRO's response to the Terms of Reference follows a short Introduction, with supporting references cited in the body of the submission provided in a final section.

We submit that CSIRO, and it's collaborators around Australia, have some capacity to continue to provide information about climate impacts and adaptation options for marine fisheries and aquaculture. There will also need to be a focus on policy and governance aspects. These research efforts will need to be combined with on-going monitoring and provision of data both from the science community and industry.

Finally, coordinated, national responses to climate change impacts and adaptation approaches are important given the value and scale of Australia's fisheries and the research sector. The National Climate Change Adaptation Research Facility and the Fisheries Research and Development Corporation have provided this research coordination role over the past decade and the need will grow as the challenges increase.

The key points relevant of this submission relevant to each TOR are:

(a): The current and future impacts of climate change on marine fisheries and biodiversity, including recent and projected changes in ocean temperatures, currents and chemistry associated with climate change;

- Research by the CSIRO and other agencies has demonstrated long term trends in the temperature and currents of the oceans around Australia, and these are projected to have greater impact in the future.
- Temperatures are warming fastest off the south-east coast of Australia, and impacts are compounded in these locations as the currents are also changing.
- Extreme events, such as marine heatwaves, and cyclones, have reduced populations of important commercial species in western and north-eastern Australia.
- Ocean acidification and falling oxygen concentrations are occurring, although the impacts have not been directly implicated in Australian fisheries changes at this time.
- Projections indicate continued warming, circulation, sea level, and pH changes around Australia.
- Although lacking a clear consensus the primary productivity of the oceans around Australia are expected to change as the oceans warms and currents change with flow-on impacts to higher trophic levels.

(b) recent and projected changes in fish stocks, marine biodiversity and marine ecosystems associated with climate change;

- Changes in the distribution and abundance of commercial fish species been documented along the east and west coasts of Australia.
- Marine habitats have been impacted by climate change all around Australia, including coral reefs, temperate kelp forests, and tropical mangroves.
- Extreme events have already had an impact on fisheries production in Western Australia.
- Models project declines in fish production in some regions of Australia for coming decades. Increases may occur in other regions.
- Ongoing monitoring will be important.

(c) recent and projected changes in marine pests and diseases associated with climate change;

- Marine species are changing distribution under climate change, and some of these species may be considered pests in new locations.

- A number of harmful viruses, bacteria and microalgae have caused significant economic harm in novel locations in the last 10 years, resulting in temporary closure of several fisheries.
- Monitoring is probably inadequate to detect introduced pests in new locations, until they become established.
- A more prepared industry, plus anticipatory monitoring both based on the likelihood of an outbreak, could reduce risks under climate change.

(d) the impact of these changes on commercial fishing and aquaculture, including associated business activity and employment;

- Extreme events that are indicative of climate change have affected fisheries and aquaculture in Australia.
- Fishing and aquaculture businesses will have to modify practices in response to climate change, from producer and along the supply chain.
- Management, regulations, and governance will have to change to maintain fishery and aquaculture sustainability.
- A range of adaptation options that reduce risk exist for both fisheries and aquaculture, at the production end, and further up the supply chain.

(e) the impact of these changes on recreational fishing;

- Recreational fishing is a large and growing sector accessing marine resources.
- Recreational fishers have observed changes potentially related to climate change.
- Recreational fishers will need to adapt to climate-related changes, and in some locations, it appears that fisher adaptation has already begun.
- Recreational fishers have a range of approaches to dealing with changes to the resources they use and are relatively flexible in responding to the impacts of climate change.

(f) the adequacy of current quota-setting and access rights provisions and processes given current and projected climate change impacts;

- Climate change will lead to new species in new areas, requiring new access rights to be considered.
- Access rights may need to adjusted when stock distribution changes.
- Changes to inflexible access rights may involve costly legal processes which could hamper adaptive management.
- Quota setting may need to be adjusted when stock productivity changes, but existing management structures can cope when appropriate information is available.
- Dynamic spatial management is a potential approach that may be more important under climate change.
- Timely responses by management to changes in stock distribution and productivity are important in areas where climate is changing rapidly.

(g) the adequacy of current and proposed marine biodiversity protections given current and projected climate change impacts;

- Projected climate change and historical modification to marine systems means that biodiversity change is inevitable.

- Protected areas are one traditional management approach that also seems to support systems in resisting range invasions.

- Mobile protected areas, using dynamic ocean management as a pathway, may be another solution to reducing impacts on biodiversity.

(h) the adequacy of biosecurity measures and monitoring systems given current and projected climate change impacts;

- Many of the issues associated with biosecurity were addressed under TOR (c).
- Current biosecurity measures, if sufficiently resourced, are also likely to be adequate under climate change.
- Australia is guided by a series of national and international guidelines. These may need to be revisited in light of climate change.
- Enhanced monitoring may be required, particularly as undesirable species and diseases may occur in new places around Australia due to a changing environment.

(i) any other related matters.

Priority research questions identified by the National Climate Change Adaptation Research Plan – Marine Biodiversity and Resources

- Priority research questions for fisheries and aquaculture have been identified by a national writing and review team as part of activity directed by the National Climate Change Adaptation Research Facility.
- Priority questions are focused on improving the policy and governance that supports adaptation to climate change in fisheries and aquaculture.
- There is no funding allocated to addressing these priority research questions at this time.

Precautionary approaches to the future may be needed under climate change

- The future is not known – fisheries and aquaculture managers will need to remain flexible and adaptable.
- Management approaches will need to be dynamic and responsive to change.

Modification of the environment as an adaptation to climate change

- Modification of the environment to reduce the impacts of climate change may be an approach that can help fisheries cope.
- The success of such approaches would be dependent on coordination across sectors and levels of government and needs a strategic approach.

Introduction

Seafood is a major contributor to global food security with aquaculture the fastest-growing animal producing sector in the world. Aquaculture currently provides for over half of the world's food fish consumption, compared with 33.8% in 2000. Global fisheries are also an important food source providing some 3 billion people with 20% of their protein. They provide direct employment for around 50 million people and 180 million people when secondary activities such as transport and processing are considered.

A large proportion of the Australian catch is comprised of high-value species such as abalone, rock lobster, tuna and prawns that are mostly exported. Overall, Australia exports over 50% of our wild fisheries catch and imports ~70% of the seafood for human consumption. While Australia's marine fisheries account for 0.2% of global marine fisheries by landed tonnage, this represents some 2% of marine fisheries by landed value. Aquaculture production from high value species such as Atlantic salmon, oysters and prawns are predominantly for national consumption.

Seafood is often seen as a "luxury" product in Australia, but many nations in our region rely on fish as a major source of animal protein on a daily basis. Thus, climate impacts on our neighbours will have flow on effects to Australia both in terms of supply of fish and possible declines in our neighbours' fisheries and hence their income and food security. Australia is immediately adjacent to one of the world's largest fishing nations (Indonesia) and to the world's two largest tuna fisheries in the Pacific and Indian Oceans. Australia has shared interests with these areas – both politically as well as through migrating species. The Indonesian annual wild fishery catch is over five million tonnes, and 3.3 million people rely directly on fishing activities for part or all of their income, the numbers rise to 6 million Indonesians if aquaculture farmers are included (FAO 2016). With regard to Pacific island countries and territories, fish is a mainstay for food security and provides 50-90% of animal protein in rural areas and 40-80% animal protein in many urban areas (Bell et al. 2009). Thus, impacts of climate change to our neighbours and their fisheries will also have flow-on effects to Australia. In this submission, we consider only the impacts of climate change on national fisheries and aquaculture businesses.

Demand for seafood is likely to increase, both domestically and in our region, placing additional pressure on sustainable production of seafood. Global landings from capture fisheries are static or declining slightly, while production from aquaculture continues to rise. This global pattern is generally mirrored in Australia (ABARES 2013), where landing from wild fisheries are generally stable, but the annual growth rate of Australian aquaculture (7%) now exceeds the annual global growth rates (~6.5%).

Recreational fishing is a growing sector in Australia with up to four million people participating per annum and catches of some species exceed commercial catches (Henry and Lyle 2001). The growth in this sector is increasing competition for access to the resource, sometimes resulting in conflict with other users, including commercial fishers. The recent Productivity Commission Review of Fisheries and Aquaculture covers some of these issues, and we do not address them here.

Australia has a strong record in fisheries management supported by robust science that positions us well to cope with the impacts of climate change. By global standards our fisheries are well managed. For example, it has been estimated that less than 15% of assessed fisheries are overfished, with an improving trend, compared to 30% globally. Australia's fisheries jurisdictions have generally adopted ecosystem-based fishery management as a policy goal. This is consistent with the growing international demand for environmentally friendly products. Spatial management and participatory or co-management are also key features of the fishery management system. In addition to climate change, the commercial sectors face a range of challenges including rising costs, the high Australian dollar, logistics and supply chain challenges, and resource allocation. "Social licence to operate" is also becoming a significant challenge, reflecting community concerns regarding the sustainability of our fisheries. This challenge has contributed to the drive for eco-certification by a number of Australia's fisheries in recent years.

Climate change also presents unique challenges for the growth of Australian aquaculture, alongside issues such as the development of a national decision support system to assist in unlocking the full potential for the sustainable growth of Australia's on-shore and off-shore aquaculture industries; progressively improving the production efficiency in existing footprints (e.g. use of alternative energy); maintaining healthy disease free stocks and efficiently managing health and welfare issues; the production of cost effective, sustainable and efficient feeds; understanding product quality, value adding and marketing; and having appropriate investment to establish new industries (species and farming regions).

Increasing marine uses (for example marine industries are worth around $50 billion per annum - NMSP 2015) can lead to tensions between sectors, and competing priorities for the same areas. Currently no arrangements exist to provide a forum for either identifying integrated strategic marine management or for setting spatial management priorities that may be required as new habitats become important as climate changes the marine environment. The science to underpin integrated management has improved markedly over the past decade, but the mechanisms for adoption of this science have been reduced with the contraction of marine planning to a sectoral level and the loss of forums to discuss their application (e.g. National Oceans Ministerial Board and the National Oceans Advisory Group in 2006, the National Oceans Office in 2008, the Marine and Coastal Committee in 2011).

Coordinated, national responses to climate change impacts and adaptation approaches are important given the value and scale of Australia's fisheries and the research sector (NMSP 2015). The National Climate Change Adaptation Research Facility and the Fisheries Research and Development Corporation have provided a research coordination role over the past decade, however, funding to address marine climate adaptation has declined. CSIRO and it's collaborators around Australia have some capacity to continue to provide primary information about climate impacts and adaptation options. The best possible management of climate impacts will also require modifications to policy and governance of our marine estate.

CSIRO response to the Terms of Reference (ToR)

(a): The current and future impacts of climate change on marine fisheries and biodiversity, including recent and projected changes in ocean temperatures, currents and chemistry associated with climate change;

Key points

- Research by the CSIRO and other agencies has demonstrated long term trends in temperature and currents of the oceans around Australia, and these are projected to have greater impacts in the future.
- Temperatures are warming fastest off the south-east coast of Australia, and impacts are compounded in these locations as the currents are also changing.
- Extreme events, such as marine heatwaves, and cyclones, have reduced populations of important commercial species in wester and north-eastern Australia.
- Ocean acidification and deoxygenation is occurring, although the changes have not been directly implicated in Australian fisheries stocks at this time.
- Projections indicate continued warming, circulation, sea level, and pH changes around Australia.
- Although lacking a clear consensus the primary productivity of the ocean around Australia are expected to change as the oceans warms and currents change with flow-on impacts to higher trophic levels

Information

Climate change is already evident in many locations around Australia

The Tasman Sea as a major global warming hotspot (Hobday and Pecl, 2014; **Figure 1**) which is also projected to experience an increase in extreme temperatures (Oliver et al. 2014). Sea surface temperatures are projected to be ~1°C warmer in the north and ~2.0°C warmer in the south-east within the next 100 years (Lough and Hobday 2011; Lenton et al. 2016). Associated with the warming the currents and productivity of south-east Australia are projected to change (Matear et al. 2013). In this area impacts on fish and fisheries are expected (Pecl et al. 2014, 2011) with changes in fish distribution most commonly observed and predicted (Sunday et al. 2015). Giant kelp forests in south-east Australia were listed as an endangered community under the *Environment Protection and Biodiversity Conservation Act 1999* (EPBC Act) in 2012 (the first marine community to be listed) with one of the major threats identified to be associated with climate change (https://www.environment.gov.au/resource/giant-kelp-marine-forests-south-east-australia).

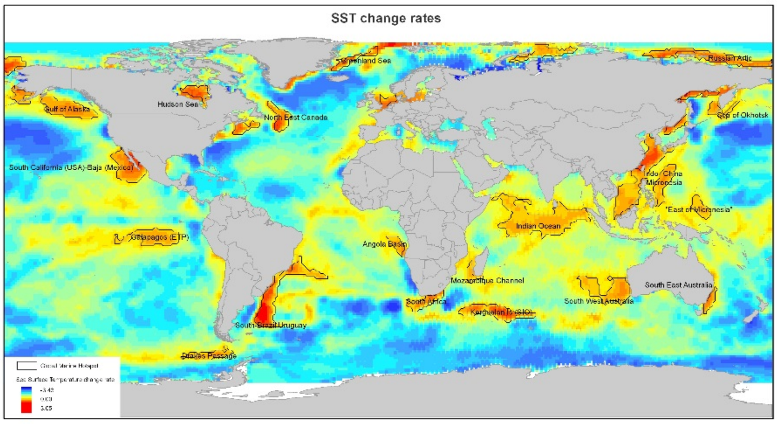

Figure 1. The fastest warming areas of the ocean over the period 1950-2000 are outlined on this map of temperature rise. Note the fast warming areas in south-eastern and south-western Australia. Source: Hobday and Pecl 2014.

Southwest Western Australia has also experienced long-term change (Caputi et al. 2015) as well as extreme events, both leading to long term ecosystem change. Wernberg et al. (2016) reported a rapid climate-driven regime shift of Australian temperate reef communities, which saw kelp forests replaced by persistent seaweed turfs. This 2011 Western Australia marine heat wave forced a 100-kilometre range contraction of extensive kelp forests and saw temperate species replaced by seaweeds, invertebrates, corals, and fishes characteristic of subtropical and tropical waters. Key fishery species were impacted: e.g. mortality of abalone; reduced recruitment of tiger prawns perhaps due to failed recruitment from impacted shallow nursery habitats (Caputi et al. 2016). This community-wide tropicalisation fundamentally altered key ecological processes, suppressing the recovery of kelp forests. These extremes can result in different signals to the long-term projections. Elevated water temperature can act as a stressor impacting the immune responses of molluscs, such as abalone, potentially increasing their susceptibility to microbial infections following extreme events. In the same region, de Lestang and Caputi (2015) suggest that as climate change models project a progressive reduction in the strength of the Leeuwin current, there may be a greater northward lobster migrations and a shift in the biomass of lobsters more towards the northern end of the fishery. The puerulus settlement of the western rock lobster fishery has also been adversely affected by changes in the timing of spawning due to warming winter temperatures (de Lestang et al. 2014).

On the west coast, the Leeuwin Current has weakened by 10–30% in the past 50 years (Pearce and Feng 2007) with strong decadal variation (Feng et al. 2010) and is predicted to weaken by a further 15% by 2060 (Sun et al. 2012). In contrast, the East Australia Current (EAC) extension has been steadily increasing in strength (Ridgway 2007; Cetina-Heredia et al. 2014) despite little change in the overall volume of the core EAC region north of the bifurcation (Sloyan and O'Kane 2015). Climate models suggest that there will be an increase in strength of 12% in the core area, and 35% in the EAC poleward extension by 2060 (Sun et al. 2012). These changes at the southern edges of the boundary currents appear to have reduced productivity and degraded the state of recipient temperate ecosystems in Western Australia (e.g. Wernberg et al. 2012), NSW (e.g. Verges et al. 2014) and Tasmania (e.g. Johnson et al. 2011). Combined with other climate-induced stressors such as increases in sea surface temperature, the dynamics and functioning of organisms along Australia's temperate coastlines may be further compromised (Coleman et al. 2014).

For most oceans around Australia warming will result in increased stratification (Capotondi et al. 2012) sometimes associated with declining oxygen concentrations (Thompson et al., 2009). In tropical regions changes in habitat quality and productivity declines are likely (Pratchett et al. 2011). Large scale bleaching events have contributed in recent decades to declining coral cover, culminating in the 2016 bleaching which has been widely reported. The Great Barrier Reef (GBR) experienced the highest temps on record in 2015/16. With rising CO_2 levels in the atmosphere the chemistry of the surface ocean will acidify, which we know will reduce organisms' ability to calcify. Changes in water chemistry, as a result of the oceans absorbing CO_2, are not well documented around Australia (Lough and Hobday 2011; Lenton et al. 2016), although the pH of the global ocean has already decreased by 0.1 (Feely et al. 2004; Sabine et al. 2004). Recent work by Lenton et al. (2016) provides an important reconstruction of ocean acidification state of the Australian region since 1850. The reconstruction highlights the longer term increase in ocean acidification but with variation around Australia.

Ocean acidification is likely to have significant consequences for marine ecosystems, especially for organisms that form calcium-based skeletons and shells, such as corals and molluscs (e.g. Hoegh-Guldberg et al. 2007; Moy et al. 2009). The GBR is one region where reduce calcification will impact corals. Recent work in the GBR (Mongin et al. 2016) highlight how the complex local structure affects the present-day chemistry of the region; results which suggest regional impacts will be experienced well before the entire GBR is adversely affected.

Drastic cuts in global greenhouse-gas emissions are necessary to curtail the impact of future change, and limit the effects of extreme climate change. However, inertia in the climate system will lead to ongoing warming (**Figure 2)** and sea-level rise throughout the 21st century, even if emissions stop today. The projections for Australian marine systems show higher temperatures, rising sea level and lower pH in the coming years (Hobday and Lough 2011; Popova et al. 2016; Lenton et al 2016).

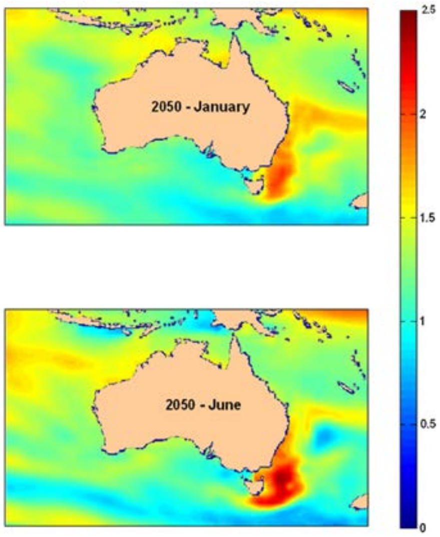

***Figure 2**. Projected warming of the south-east Australia hotspot for summer and winter in 2050 compared to a baseline of 1990, based on an ensemble mean of global climate models (Source Frusher et al. 2014)*

Climate impacts on aquaculture

The key environmental variables affecting aquaculture have been identified for some time (Lough and Hobday 2011; Lenton et al. 2016), such as extreme water temperatures, low oxygen levels and shifts in temperature regimes that are likely to affect growth, survival and abundance of various aquaculture species. South-east Australia is a climate warming hotspot (Hobday and Pecl, 2014; Popova et al 2016), while extreme events occur all around Australia (Hodgkinson et al. 2014; Oliver et al. 2015). Recent work on marine heatwaves has shown the frequency and impact of these extremes is rising (Oliver et al. 2014). Oliver et al. 2014 also showed that the extreme sea surface temperatures (SST) are projected to increase in the Tasman Sea with a greater than 50% chance that annual maximum SST will increase by at least 2°C in this hotspot and that this change is significantly different than that which might be expected from normal variation within a stable climate. For the Tasmanian coast, it is expected the water will continue to warm faster than the rest of the world as more warm East Australian Water moves southward with a strengthening EAC and increased generation of its eddies (Matear et al. 2013). The increased EAC and its eddies will warm the water along the east coast of Tasmania and help subtropical species move south (increasing the connectivity along East Australia) and the warming will make the environment more suitable for more northern species.

The impacts of ocean acidification (OA) for aquaculture are less certain, and remain a subject of interest for vulnerable life history stages of calcifying organisms. Acidification of estuarine waters can also be caused by runoff from acid sulphate soils (ASS), which occur on floodplains worldwide. Calcifying organisms exposed for even short periods (1-2 mo) to runoff from ASS suffer 80% mortality and slowed growth. These land-derived effects have largely been ignored, and may need attention in some areas. Richards et al. (2015) examined the implications of OA on prawn and scallop fisheries in Queensland and compared the adaptive capacity of wild and aquaculture fisheries, showing that wild populations of prawns and scallops appear to be more vulnerable to OA and climate-induced stresses than aquaculture-based populations. They note that aquaculture is likely to be more viable in the long term than the wild fishery as aquaculture facilities allow water quality monitoring and modification to avoid excessive exposure to temperature and OA changes in the ocean.

Climate related impacts on ecosystems are expected around Australia

Coastal areas in tropical Australia are projected to experience more intense storms and severe weather events that can reduce fishery access, as well as destroy or severely damage fisheries assets and infrastructure such as landing sites, boats and gear (Holbrook and Johnson 2012). Increased storm and wave activity may reduce (i) the number of days commercial and recreational fishers can fish, (ii) access to some locations for both boat and shore-based fishers, and (iii) the seasonal availability of fish. Tropical cyclones have the capacity to destroy inshore critical nursery habitat for fishery species and cause recruitment failure in subsequent years (Loneragan et al. 2013). An increase in the frequency of category 4 and category 5 cyclones increases the likelihood of regular major impacts to shallow coastal regions that may cause the loss of habitats such as seagrass and mangroves and restrict their reestablishment.

With climate change southern Australia is likely to see enhanced wind and wave events (Hemer et al. 2013), while more intense extreme wind events are projected for north-east Australia. Higher sea levels will exacerbate the inundation of coastal fishing infrastructure, including port and processing facilities (Lenton et al. 2016). However, in southwest Western Australia there has been a decrease in winter storms since the 1970s and this trend is projected to continue (Indian Ocean Climate Initiative 2012) which should result in an increase in days available for fishing. As for many other environmental variables the projections of sea level rise vary around Australia with important regional differences due to the interaction of global sea level rise with the local ocean dynamics and winds (Lenton et al. 2015).

Tropical coastal ecosystems across northern Australia are characterised by large expanses of coastline with very low relief and slope. Supra-tidal saltpans and wetlands cover hundreds of square kilometres adjacent to the beachline. They are cyclically inundated during the wet season. A 20-30 cm increase in sea level will cause the tidal inundation of saltpan and wetland habitat with saltwater incursion to hitherto freshwater habitats and a change in inundation regime of saltpans. The impact of these changes on fisheries is unknown; estuarine conditions may expand and enhance nursery habitats for some species. The annual cycle of floodwater inundation will change, however, with impacts on nutrient cycles in tropical wet/dry rivers and estuaries (Burford et al. 2016).

(b) recent and projected changes in fish stocks, marine biodiversity and marine ecosystems associated with climate change;

Key points

- Changes in the distribution and abundance of commercial fish species been documented along the east and west coasts of Australia
- Marine habitats have been impacted by climate change all around Australia, including coral reefs, temperate kelp forests, and tropical mangroves.
- Extreme events have already had an impact on fisheries production in Western Australia
- Models project declines in fish production in some regions of Australia for coming decades. Increases may occur in other regions.
- Ongoing monitoring will be important

Information

Observed impacts on Australian fish and ecosystems

Changes in fish and invertebrate distribution have been widely reported around Australia. These changes are primarily related to increases in water temperature and changes in ocean currents (Booth et al. 2011; Madin et al. 2011; Sunday et al. 2015). For example, Last et al. (2011) reports some forty-five fish species, representing 27 families (~30% of the inshore fish families occurring in the region) exhibited poleward distributional shifts in Tasmania.

Observed impacts on marine species around Australia have been reported from a range of trophic levels (Frusher et al. 2014). At the base of the food chain, a 50% decline in the biomass of the spring phytoplankton bloom and growth rate (via chlorophyll a) between 1997-2007 has been reported from eastern Tasmania (Thompson et al. 2009), where cold water zooplankton have also become less common (Johnson et al. 2011), which is correlated with a change in small pelagic fish composition (McLeod et al, 2012). Growth of southern rock lobster, positively related to water temperature, has increased in southern Tasmania, however, recruitment of juvenile lobsters is negatively related to temperature and has concomitantly declined (Pecl et al. 2009; Johnson et al. 2011). Declining growth rates in one coastal fish (banded morwong), particularly at the warm end of its range in Australia suggest that the direct metabolic effects of increasing temperatures on this species may lead to declining productivity in the north and range contraction to the south (Neuheimer et al. 2011).

Three related projects funded by the National Climate Change Adaptation Research Facility (NCCARF) and the Fisheries Research and Development Corporation (FRDC) examined the impact of climate change on commercial fisheries in the southeast (Pecl et al. 2014), north (Welch et al. 2015) and west (Caputi et al. 2014) of Australia. The southeast project provided a detailed assessment of how commercially targeted species in State and Commonwealth fisheries may be affected by climate change, and a similar approach was followed in the Northern Australia report, which provides an overview of all commercial species and undertakes a case study analysis of five species. The Western Australian project carried out a basic review of management arrangements in terms of robustness under predicted changes and identified the need for flexibility in fisheries management to rapidly respond to variability. Five species of commercial invertebrates were shown to be impacted by the extreme inshore temperatures; both directly and via impacts on their habitat (Caputi et al. 2016). Abalone suffered direct mortality due to high water temperature and low levels of dissolved oxygen; mortality was highly location specific. Scallops suffered a recruitment failure due to mortality of juveniles and adults and the fishery was closed in the year subsequent to the heatwave to protect the remnant stock. Prawn recruitment was impacted by temperature; both positively and negatively. In Shark Bay, warmer temperatures enhanced the recruitment of king and tiger prawns from juvenile habitats to the offshore fishery, probably as temperatures were optimal for growth of larvae and juveniles. Further north in Exmouth Gulf inshore waters are warmer normally and the increase in temperature caused a collapse in tiger prawn recruitment. Elevated temperature of shallow inshore waters pushed inshore habitats and resident prawns above optimal temperatures for growth and survival causing prawn mortality and the possible loss of seagrass habitat.

These fishery impacts in Western Australia highlight that the impacts of climate change (e.g. elevated water temperature) may be critical to one phase in the life history of a species, while having little impact on the phase that is fished. It is clear that those species with an inshore larval/juvenile phase may be impacted greatly by temperature extremes in shallow inshore habitats (e.g. < 5 m deep) with the interaction of an abnormal incursion of warm water enhanced by direct solar radiation during periods of extreme-heat days that are projected to increase in frequency. Abnormal shallow-water temperatures above physiological tolerances may cause direct mortality of fishery species, or loss of critical nursery habitat.

Projected changes on fish and ecosystems

Global models being used to project changes in marine ecosystems and fisheries around the world indicate that all Australian waters are expect to see a 10%, or greater, reduction in total fish production (Blanchard et al. in review). In many locations this translates into a reduction in catch potential, although shifts in species distributions in the southern corners (east and west) of Australia may see total catches maintained, but made up of different species than today (Cheung et al. in press). Modelling dedicated to the examination of potential futures for Australia's marine ecosystems have similar findings. For example, in south eastern Australia, ecosystem models (Fulton and Gorton 2014) indicate that while some pelagic species increase in abundance under climate change, demersal species (which are often the chief target species of Australian fisheries) are more vulnerable, especially to the combined effects of climate change and other pressures on Australia's coastal ecosystems (e.g. increasing urban and industrial development) (**Figure 3)**. These models indicate that under the highest levels of climate change considered by the IPCC there is the potential for a regime shift in south eastern Australia, with habitat for some of the important species disappearing by the second half of the century. Under more moderate levels of climate change these species are better able to adapt.

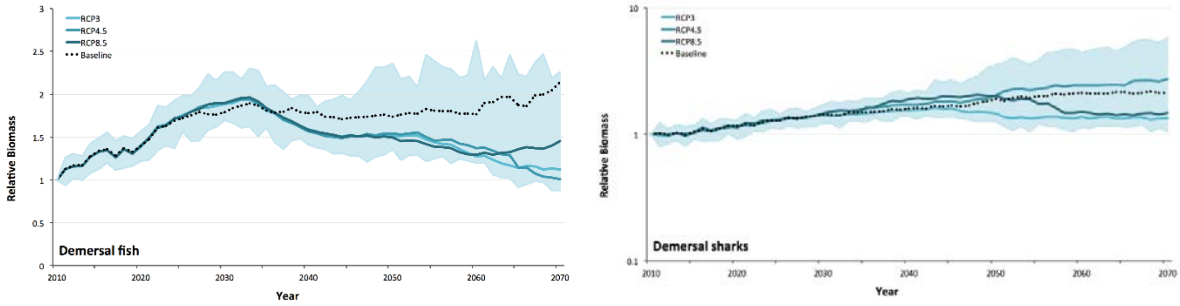

Figure 3. Example output from a system model for south-east Australia (SEAP-Atlantis) showing the biomass of demersal fish and demersal sharks to the year 2070 under different emission scenarios. The lighter shaded area is the total range of climate futures. Source Fulton and Gorton 2014.

System models used to explore potential futures for Australian fisheries and aquaculture suggest some of the biggest challenges for marine ecosystems will be in the ability of human users to adapt their behaviours and management actions to allow ecosystems the maximum potential to adapt to the environmental changes (Fulton and Gorton 2014). Of the many barriers to adaptation identified for fisheries and aquaculture only one was biological (the evolutionary and adaptive capacity) the rest were human behaviours:

- Human behavioural flexibility is needed for adaptation, but is not a universal personality trait. Behavioural flexibility can also be discouraged by social or cultural norms;
- Governance and regulation can constrain adaptation, preventing the flexibility needed for adaptation, and management inertia can slow responses, reduce adaptive capacity and cause economic and social hardship;
- Market and other economic drivers often act on short time frames and may not align with requirements for long term adaptation;
- Available technology may not match what is required or may encourage practices that are ultimately maladaptive;
- Remaining gaps in understanding can mean that insufficient information is available for good adaptive management.

Model-based work done so far indicates that the most effective forms of management will require integration across different sectors. Existing sector focused methods will be insufficient, especially if climate change goes beyond the more moderate scenarios considered by the IPCC (Fulton and Gorton 2014).

Overall, changes in fish distribution, abundance, migrations, and physiology have been document or projected to occur. Where these species are utilised in fisheries, or aquaculture, flow-on impacts on industry are expected. Pecl et al. (2014) developed an objective, flexible and cost effective framework for prioritising future ecological research and subsequent investment in adaptation responses using key species within the fast warming region of south-eastern Australia. This approach has enabled fisheries managers to understand likely changes to fisheries under a range of climate change scenarios, highlighted critical research gaps and priorities, and assisted marine industries to identify adaptation strategies that maximise positive outcomes. This approach could be widely applied around Australia.

The ability of Australian fisheries management processes to adapt to all these changes are untested and steps need to be taken now to ensure appropriate management practices which will ensure sustainable fishing into the future.

Monitoring systems

A range of dedicated and ongoing programs provide information on the state of the ocean, biological responses, and fisheries-relevant information. Here we note the existence of some important programs which have provided insight into the impacts of climate change on the ocean, species and ecosystems.

CSIRO understands that other submissions will deal more broadly with the information collected by citizen science projects (University of Tasmania) and fisheries (FRDC).

The Integrated Marine Observing System (IMOS), is the principal Australian body responsible for collection of physical and chemical marine observations (e.g. Lynch et al. 2014). IMOS facilities collect detailed information for many regions of Australia, and have provided a very important data stream around Australia. IMOS supports additional products, such as "Plankton 2015", an assessment of the state of the oceans around Australia using plankton as indicators of ecological change which informs marine managers, scientists and the public of changes at the base of the marine food web and their potential implications for higher trophic levels and dependent industries and people.

The Great Barrier Reef is extensively monitored through programs including the Great Barrier Reef Marine Park Authority (GBRMPA) Marine Monitoring Program, the Australian Institute of Marine Science (AIMS) long term monitoring program and the Joint Field Management Program (Queensland-GBRMPA) as well as IMOS. A companion citizen science project (Eye on the Reef) is increasing the knowledge base for over 600 reefs.

Without an ongoing commitment to monitoring, timely information about the state of the ocean will not be available to support adaptive management on fisheries and aquaculture.

(c) recent and projected changes in marine pests and diseases associated with climate change;

Key points

- Marine species are changing distribution under climate change, and some of these species may be considered pests in new locations.
- A number of harmful viruses, bacteria and microalgae have caused significant economic harm in novel locations in the last 10 years, resulting in temporary closure of several fisheries.
- Monitoring is probably inadequate to detect introduced pests in new locations, until they become established.
- A more prepared industry, plus anticipatory monitoring both based on the likelihood of an outbreak, could reduce risks under climate change.

Information

Climate change is leading to a redistribution of marine species, altering ecosystem dynamics as species extend or shift their geographic ranges polewards with warming waters (**Figure 4)**. In marine systems, range shifts have been observed in a wide diversity of species and ecosystems and are predicted to become more prevalent as environmental conditions continue to change (Poloczanska et al. 2013). The effect of range shifts on socio-economic aspects is often overlooked, yet has the potential to have positive and/or negative effects on economic activities, human health and ecosystem services (Madin et al. 2012).

Changes in the distribution of marine pests and algal blooms

There are over 250 introduced marine plants and animals established in Australian waters (see marinepests.gov.au). Some have hitch-hiked to Australian waters on the hulls of vessels of all types from yachts to commercial ships, or in their ballast water. Others have been introduced to support local aquaculture, with the aquarium industry another vector. Some have displaced our native species from their habitats, modifying ecosystems and effecting marine industries (Bax et al. 2002, Ross et al. 2002, Hayes & Sliwa 2003). Many of the species introduced to Australia, however, do not become established (that is survive long enough to reproduce, complete a full life cycle and establish a population), and most established species do not become widespread or invasive in terms of their distribution and numbers. This is largely because environmental conditions at introduction sites may not be suitable and/or native species outcompete species before they can become established and invasive. Many species will remain restricted to areas in ports or other semi-enclosed areas close to their point(s) of introduction. Under climate change, however, some of these pests may change distribution, or become more abundant in their current range.

__Figure 4.__ Hypothetical examples of range shifts. Source Madin et al. 2012.

New incursions are inherently difficult to predict, and the history of introductions is replete with unexpected events at the point of establishment that may occur decades later when changed environmental conditions facilitate their spread. This highlights the need for early detection, with some states developing programs that encourage the public to report unknown species that may potentially be introduced and invasive. Ongoing monitoring for introduced species is cost and labour intensive, and as a result monitoring effort has varied considerably between jurisdictions and is mostly limited, despite concentrated efforts to develop monitoring systems (DoAWR 2015). As a result, any limitations to Australia's national and local prevention arrangements is likely to be identified through the establishment of an introduced species. The development of new technologies may provide more viable monitoring options in the future which are likely to not only provide for early detection, but also inform regulation development.

Australia introduced voluntary ballast water management arrangements in 1991 for vessels entering Australian waters and Victoria introduced comprehensive ballast water arrangements for vessels entering their ports in 1994. It is now compulsory for all international vessels to manage their ballast water according to Australian ballast water management requirements. In the event of a marine pest incursion of national significance, the Consultative Committee on Introduced Marine Pest Emergencies would be convened. This national technical forum, consisting of members from the Australian, state and Northern Territory Governments, would provide advice on the feasibility and coordination of a national response as per the Emergency Marine Pest Plan (see www.marinepests.gov.au/national-system/how-it-works/Emergency_management/). A recently concluded review of Australian Government policy on introduced species, together with implementation of the new *Biosecurity Act 2015*, should provide an improved and more nationally consistent approach to domestic policy and legislation relating to marine vessels.

Some range-changing native species may be considered pests (van Putten et al. 2015), with considerable environmental impacts, such as the long-spined urchin in Tasmania (Ling et al. 2012; Johnson et al. 2011). Marine algae are also changing their distribution, and single-celled species can increase dramatically in some locations, which can result in deleterious effects for local marine ecosystems. Harmful algal blooms (HABs) are a well-known global phenomena with potentially lethal effects on humans that eat affected seafood. There are more than 80 HAB species known from Australian waters (Hallegraeff, 2002). Most countries, including Australia, have well developed monitoring programs that ensure seafood is safe to eat. The impact of HABs on the fishing and aquaculture industries can run in to millions of dollars with the 2012 case in Tasmania a good example. The closure of several fisheries along the east coast of Tasmania due to a bloom of *Alexandrium tamarense* in the spring of 2012 is estimated to have cost upwards of $23 million (Campbell et al. 2013). A prolonged and extensive bloom of *Alexandrium tamarense* along the east coast of

Tasmania also occurred in 2015–2016 contaminated mussels, oysters, scallops and ultimately rock lobsters. Shellfish harvest areas were closed from late July to late November 2015 and some wild fisheries blocks remain closed. During the period 2011-2016, blooms of the algae *Karenia mikimotoi* resulted in major fish kills in South Australia in 2014, while the algae *Chaetoceros* sp. bloomed in 2015 in Western Australia with similar results.

There is clear evidence of HAB species expanding their range (Thompson et al. 2008) and that at least some expansions are likely related to climate (e.g. Kibler et al. 2015). There are a number of HAB expansions, for species like Ciguatera, that significantly the increase health risks for Australians (e.g. Farrell et al. 2016). The likelihood and magnitude of these risks are not well established. The lack of a national risk assessment combined with monitoring largely restricted to regions of known risk potentially exposes Australians and our export markets to novel outbreaks (Campbell et al. 2013).

Changes in disease occurrence or prevalence

Disease, potentially related to climate change, has emerged as a real threat in recent years in other countries (Leung and Bates 2012). Australia's wild-capture fisheries, aquaculture, recreational fisheries and traditional fisheries are fortunate to be free from many diseases that occur overseas, providing us with a competitive advantage in both production and trade. In Australia there are 47 reportable aquatic diseases (23 for finfish, 13 for molluscs, 11 for crustaceans), 34 of which are identified as exotic (see http://www.agriculture.gov.au/animal/aquatic/reporting/reportable-diseases). The majority are associated with freshwater species rather than marine species. Australia has a reporting system for aquatic animal diseases of national significance. All the diseases currently reportable to the World Organisation for Animal Health and any other aquatic animal diseases of national significance are included on Australia's National List of Reportable Diseases of Aquatic Animals (www.agriculture.gov.au/animal-plant-health/aquatic/reporting).

While the number of aquatic animal species and the absolute number of aquatic animals being farmed in Australia is increasing, new diseases caused by emerging infectious agents (e.g. Atlantic salmon rickettsia-like organism (Corbeil et al. 2005); abalone herpesvirus (Corbeil et al. 2010); oyster oedema disease (Crockford and Jones 2011); ostreid herpesvirus (Frances et al. 2011) continue to threaten the sustainability of significant enterprises, and biosecurity agencies have a critical role to play in support this expanding industry. There have been several examples of disease outbreaks in south-eastern Australia which have threatened aquaculture operations. Climate change is a contributor, for example elevated water temperature can act as a stressor impacting the immune responses of molluscs, such as abalone, potentially increasing their susceptibility to microbial infections.

In New South Wales, disease mitigation programs are broadly implemented and well regulated, although damaging epizootics and new diseases (e.g. Pacific Oyster Mortality Syndrome; POMS) continue to occur. In Victoria, the last outbreak of abalone viral ganglioneuritis was in 2010 – however, it was detected in a commercial population in Tasmania in 2011. An outbreak of POMS in 2016 in Tasmania confirmed establishment of the virus in the state (Gibson, 2016) which will have long-lasting effects on oyster aquaculture operations. The response to the detection of the virus has included restrictions on the movement of oysters onto oyster farms while testing for the disease across the state was conducted. Ongoing management will need to include development of strains of oysters that are resistant to the disease and state agencies are working with industry to develop options for future management of oysters now that that the virus is established (see http://dpipwe.tas.gov.au/biosecurity/aquatic-pests-and-diseases/aquatic-biosecurity-threats/poms).

Experience and theory would suggest that as temperatures increase and aquaculture operations become more common there will be more frequent outbreaks of disease. Since 2008 there have been at least 13 new outbreaks of diseases in wild fisheries and aquaculture species in Australia that are consistent with this hypothesis (2008: White tail disease in the giant freshwater prawn (Queensland); 2008: Infectious hypodermal and haematopoietic necrosis virus (Queensland); 2008: Abalone viral ganglioneuritis in wild-caught abalone (Tasmania); 2010: Ostreid herpesvirus-1 μVar in Pacific oysters (New South Wales); 2010:

Edwardsiella ictaluri in catfish (Northern Territory); 2011: Abalone herpesvirus in farmed abalone (Tasmania); 2012: Megalocytivirus in farmed ornamental fish (Queensland); 2012: Pilchard Orthomyxovirus in farmed Atlantic salmon (Tasmania); 2013: New yellow head virus genotype in farmed prawns (Queensland); 2014: *Edwardsiella ictaluri* in catfish (Queensland); 2015: *Penaeus monodon* hepatopancreatitis (Queensland); 2015: *Bonamia exitiosa* in native oysters (Victoria); 2015: *Bonamia exitiosa* in native oysters (South Australia); and 2016: Ostreid herpesvirus-1 µVar or Pacific Oyster Mortality Syndrome (POMS) in Tasmania (Crane and Slater 2016). POMS had a serious impact on NSW oyster farming commencing in 2010 and the 2016 outbreak in Tasmania has also been a significant problem for the local oyster industry with some operations incurring substantial finance losses (Davis 2016). It has also restricted the supply of seedstock to the broader industry particularly in South Australia (Davis 2016).

Known diseases of aquatic animals that are endemic to Australia include nervous necrosis virus in finfish, gill associated virus (GAV; yellow head virus (YHV) genotype 2) and other YHV genotypes in prawns, Bonamia in edible oysters, oedema oyster disease in pearl oysters, ostreid herpesvirus type 1 microvariant (OsHV-1 uVar) in Pacific oysters, *Edwardsiella ictaluri* in catfish, *Streptococcus agalactiae* in grouper, and abalone viral ganglioneuritis caused by abalone herpesvirus (AbHV) (Crane and Slater 2016). The outbreak of AbHV in wild stocks of abalone has been suggest to be a result of transmission from aquaculture stocks of abalone (Prince 2007; Handlinger 2007).

(d) the impact of these changes on commercial fishing and aquaculture, including associated business activity and employment;

Key points

- Extreme events that are indicative of climate change have affected fisheries and aquaculture in Australia.
- Fishing and aquaculture businesses will have to modify practices in response to climate change, from producer and along the supply chain.
- Management, regulations, and governance will have to change to maintain fishery and aquaculture sustainability.
- A range of adaptation options exist for both fisheries and aquaculture, at the production end, and further up the supply chain.

Information

Australian fisheries impacts and adaptation research has been guided by the Marine National Adaptation Research Plan (NARP) (Mapstone et al. 2010), and the National Action Plan for Fisheries (DAFF 2010); both have a strong focus on ecosystem and industry adaptation. Adaptation options exist for a range of marine species and their fisheries (Pecl et al. 2009; Hobday and Poloczanska 2010), such as maintaining freshwater flows to keep estuaries open and functioning for black bream fisheries in Victoria (Jenkins et al. 2010). For southern species found on the continental shelf, however, options may be more limited, as suitable habitat may not be present in future. For example, a southward shift in fishery activity has already been reported for Tasmanian southern rock lobster (Pecl et al. 2009), but given the spatial flexibility in the northern fleet, adaptation to climate change is considered possible by most participants for the short-term. Translocation of wild species to more suitable growing regions may be possible for some high value species, and maintain production in the face of declining recruitment and has been trialled for southern rock lobster (Green et al. 2010).

Ecosystem models used to consider potential futures for Australia's south eastern fisheries and aquaculture indicate that sustainable fisheries will be possible under climate change. However, it will likely require a change in species mix, including more invertebrates and pelagic fish (Fulton and Gorton 2014). The fisheries will also still be profitable, but the employment projections are more mixed. If there are strong restrictions on the use of large vessels, which can shift with species then the landings, value and economic health can be negatively impacted. However, if such large vessels can be used (with suitable management in place for them to remain sustainable) the economic health of fisheries is good (potentially improving substantially versus the current state). However, employment will contract as smaller boats - which are socially tied and do not have the capacity to shift with stocks or ride out the potential increases in variability – leave fisheries (Fulton and Gorton 2014). If this outcome is to be avoided the smaller fishers would need additional livelihood support to help their capacity to shift as required.

There has been emphasis in both research and adaptation efforts at the production end of supply chains with impacts further along the chain generally overlooked (Hobday et al. 2014; 2015; Fleming et al. 2014). Lim-Camacho et al. (2015) argued that a holistic biophysical and socio-economic system view of seafood industries, as represented by end-to-end supply chains, may lead to an additional set of options in the face of climate change, thus maximizing opportunities for improved fishery profitability, while also reducing the potential for maladaptation. They showed there were a range of actions targeting different stages of the supply chain, although most were related to the production end of the supply chain. There are chain-wide adaptation strategies that can present win-win scenarios, where commercial objectives beyond adaptation can also be addressed alongside direct or indirect impacts of climate. Likewise, certain adaptation strategies in place at one stage of the chain may have varying implications on other stages of the chain (**Figure 5)**.

The supply chain implications and adaptations should not be considered in isolation as they are directly connected to coastal community socioeconomic vulnerability to climate change. A direct relationship can be found between, for instance, the relative population size of coastal communities, their dependence on the marine resources, and their relative vulnerability (Metcalf et al. 2015). Even though small communities can be strong in some important aspects of the human, social and financial domains, putting them in a good position to deal with some changes, requires scale-appropriate and context-specific policies to address identified socio-economic vulnerabilities of coastal communities (van Putten et al. 2016).

Attention to economic aspects can also help fisheries cope with climate change. The move of some fisheries such as the northern prawn fishery and the western rock lobster fishery (Caputi et al. 2015) to target the more conservative maximum economic yield level of fishing provides increased ecological resilience in the stocks.

Aquaculture businesses are seeking to reduce dependence on wild-caught feed, driven by social and market pressures more than climate change (Farmery et al. 2015). Policy changes aimed at reducing greenhouse gas emissions have lapsed in recent years (e.g. carbon tax) and so costs that increase the cost of production, packaging and distribution activities have not yet occurred (Cochrane et al. 2009). In preparation for carbon emission labelling, the energy budget of some products such as lobsters and prawns has been derived (e.g. Farmery et al. 2015; van Putten et al. 2015), and the industry is probably ahead of the game at this stage.

The ecosystem models used to consider potential futures for south eastern Australian aquaculture reinforce the importance of the interaction of the kind of aquaculture and the degree of climate change (Fulton and Gorton 2014). Fin-fish aquaculture is less impacted if offshore platforms become more widely used (if not then species like salmon may not be farmable by mid-century); bivalve aquaculture remains important if heat and acidification tolerant strains are found; and if onshore or closed system aquaculture can be facilitated within landscape and coastal planning. Aquaculture may also respond by growing vulnerable life stages in more benign environments and then moving them to traditional regions, as is occurring on the west coast of the United States. The ecosystem models indicate that shallow water aquaculture will be more heavily pressured – both by climate but also competition with other (increasingly common) coastal uses (Fulton and Gorton 2014).

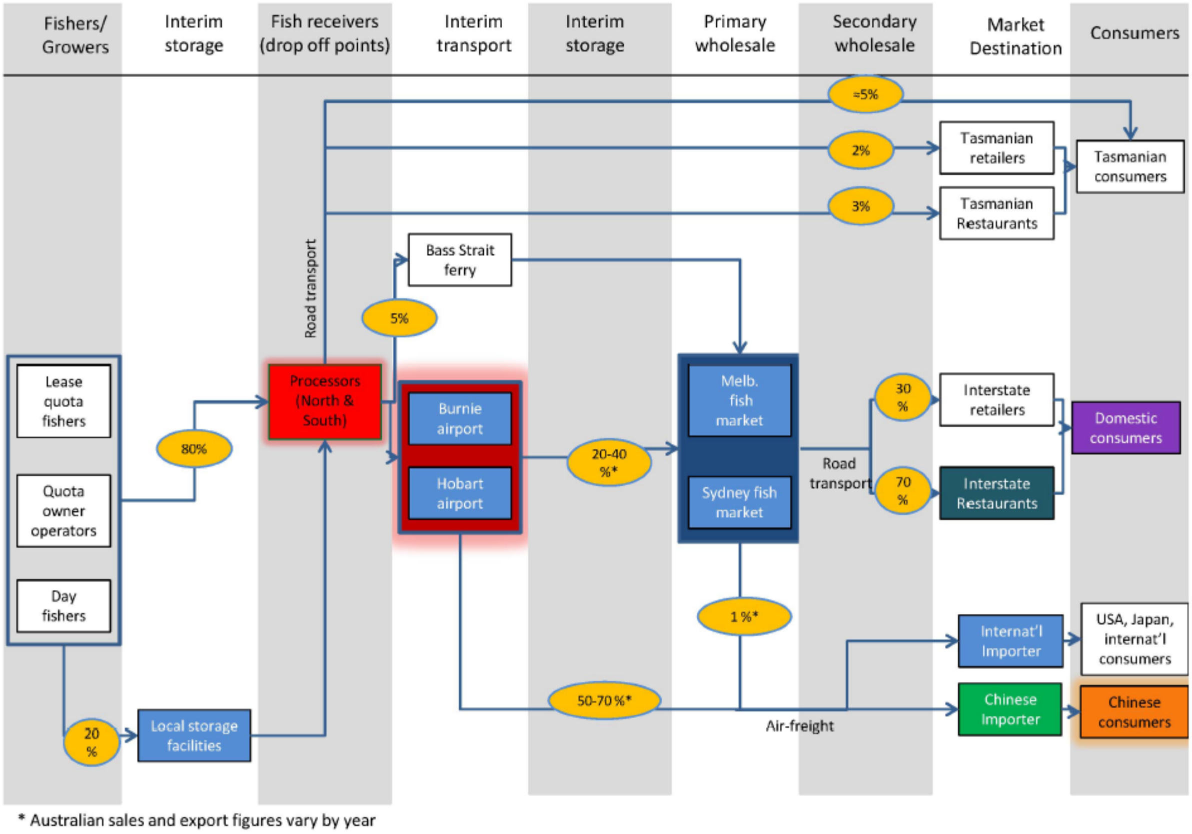

Figure 5. . An example supply chain, showing the flow of seafood product from producer (left hand side) to consumer (right hand side). Climate change and extreme events can disrupt the supply chain and adaptation may be needed to maintain product flow. Source Plaganyi et al. 2014.

Environmental and non-environmental extrinsic factors have already affected the way aquaculture businesses are undertaken. For example, eco-certification and consumer demands have seen substantial efforts to reduce the level of fish in in the feedstock used in industries such as salmon and prawns. Environmental extremes, such as cyclones and marine heatwaves, provide a window into the future. These lessons for businesses have prompted new thinking. For example, seasonal forecasts are now used in a several industries (Spillman & Hobday 2014; Spillman et al. 2015). Overall, research has shown that this sector is dynamic and flexible, and should adapt well, provided information and financing is available.

(e) the impact of these changes on recreational fishing;

Key points

- Recreational fishing is a large and growing sector accessing marine resources.
- Recreational fishers have observed changes consistent with climate change.
- Recreational fishers will need to adapt to climate-related changes, and in some locations, it appears that fisher adaptation has already begun.
- Recreational fishers have a range of approaches to dealing with changes to the resources they use and are relatively flexible in responding to the impacts of climate change.

Information

In Australia over 3.4 million people take part in recreational fishing each year (Savage and Hobsbawn 2014). The social and cultural importance of recreational fishing to participants is well known. Similarly, the importance of recreational fishing to the economy has been well established. Recreational catches have increased globally and in Australia over the past decades, due in part to population increases but also to technology improvements (van Putten et al, in review).

Annual recreational fish catches in Australia are now approximately 30,000 tonnes (Colquhoun, 2015). In some regions and in some Australian fisheries, the recreational harvest now exceeds the commercial harvest and can lead to localised depletion (Stuart-Smith et al. 2008). Competition for fish between recreational and commercial fishers, and differences in beliefs about appropriate management objectives (Jennings et al. 2016) can create resource sharing issues.

To examine possible impacts of climate change on recreational fishers, Gledhill et al. (2015) worked with recreational spearfishers to collate and examine spearfishing club data collected from competitions held throughout south-eastern Australia from the 1960s until the present. The data proved suitable for demonstrating change in coastal fish communities, some of which were consistent with expectations given a warming climate over the period considered. An attitudinal survey of divers showed most had noticed some change in the environment and were adapting autonomously.

Overall, recreational fisheries have received less attention with regard to adaptation efforts. As noted by Holbrook and Johnson (2012), recreational fishers will have flexibility to adapt to changes in fish distribution and seasonality, with options to target alternative species, fish at different times, or move to new fishing locations in the vicinity. The limited work to date suggest that most recreational fishers will keep fishing in the same areas, just adapting to new species or abundances (Gledhill et al. 2015; van Putten et al. in review). In areas of southern Australia, where new species are occurring, fishers are quick to take advantage of opportunities (Robinson et al. 2015). However, not all recreational fishers will adapt to change in the marine environment in the same way or at the same time (van Putten et al. in review). Some marine resource users might adapt early while others adapt later, for instance, when the tools and social pressure for adaptation have become more embedded. An aspect that influences adaptation responses and timing is the knowledge that users have about the changes happening around them and their own personal observations of this change.

Knowledge about the nature of change is one factor that will help people gain the capacity to manage and deal with change, and ultimately protect and conserve the values that are important to them. Local knowledge and forethought about potential impacts and changes in the marine environment is valuable in enabling critical adaptation, thereby improving recreational fisheries and coastal zone management and sustainability (van Putten et al. in review). Foresight into potential adaptation paths and timing is also essential to enable appropriate and efficient planning for infrastructure provision, especially in small coastal communities where financial resources may be too scarce to allow for adaptation to potentially rapidly changing use patterns.

Regardless of adaptive behaviour it is possible that the satisfaction level with fishing as a consequence of reduced catch quantities will decrease. Reduced satisfaction with fishing may result in fewer active fishers as they seek other alternative recreation activities in the marine space. Any such change may reduce fishing pressure on a declining species – while this may be environmentally beneficial, the social and economic consequences are largely unknown. Given the importance of recreational fishing to coastal communities, this aspect of adaptation deserves more attention.

(f) the adequacy of current quota-setting and access rights provisions and processes given current and projected climate change impacts;

Key points

- Climate change will lead to new species in new areas, requiring new access rights to be considered.
- Access rights may need to adjusted when stock distribution changes.
- Changes to inflexible access rights may involve costly legal processes which could hamper adaptive management.
- Quota setting may need to be adjusted when stock productivity changes, but existing management structures can cope when appropriate information is available.
- Dynamic spatial management is potential an approach that may be more important under climate change.

- Timely responses by management to changes in stock distribution and productivity are important in areas where climate is changing rapidly.

Information

The majority of Australia's fishery species are considered sustainably managed, however, future climate change may impact industry profitability (Hobday et al. 2008; Pecl et al. 2011; Norman-Lopez et al. 2011). For example, pelagic fishes such as sharks, tuna and billfish are projected to move further south on the east and west coasts of Australia (Hobday 2010), which may change the distribution of fishing vessels amongst east coast ports. These changes may lead to shifts in overlap between different species, which has implications for fisheries bycatch management (Hartog et al. 2011).

These changes in distribution and abundance of species can also influence quota setting and access rights provisions and processes. These are two separate management issues, and we address them separately here.

Quota setting for fisheries

Climate change can affect two main inputs in quota systems: (i) the setting of target and limit reference points and (ii), the reliability of forward projections from management strategy evaluation models. The latter should, where possible, acknowledge and incorporate current and projected climate change impacts in their operating models, so as to provide more accurate projections of stock status in to the future. The former will need to be conservative to consider species resilience in the face of change. The updating of reference points has been suggested as the best practice means of adapting current management strategies for changing climate conditions (Brown et al. 2012), however, the modified reference points will be hard to estimate given variation in monitoring data and short time series for many species.

More generally, it will be important to consider the nature of the perceived impact. Changes in spatial availability, increased natural mortality and/or decreased reproductive potential due to stress, all have different implications in the context of quota setting. For example, a change in spatial distribution of a species or stock may result in local changes in availability, without the overall stock status being compromised. From a species sustainability perspective, quotas could remain unchanged (although there may be pressure for access rights in response to a shifting stock), but local economic objectives may be compromised. As such, while the outcome of an overall stock assessment may be unchanged, local assessments may be preferred so that quotas may be determined based more directly on local availability. Alternatively, if the species sustainability is compromised due to increased stress, then this should be accounted for by ensuring that operating model and assessment inputs and assumptions (such as natural mortality and stock-recruitment parameters) are not temporally static, but rather reflect the perceived stresses being experienced by the stock.

To this end, the challenge will be to translate current and future projected climate change impacts into currencies (e.g. reproductive success, changes in natural mortality) that directly reflect the nature of these impacts on the stock. This is simpler when the impact is limited to changing spatial distribution. In the absence of direct estimates of such impacts, they will either have to be indirectly estimated from other projected environmental indicator changes, or catered for by introducing conservative estimates of parameters, and/or building in high levels of uncertainty.

Access rights for fisheries

With regard to access rights, provisions and processes, proportional distribution of rights should be relatively unaffected by climate change. If climate change impacts have the potential to compromise the availability or sustainability of a species/stock, this should impact on quota setting rather than on access rights.

Inflexible access rights where any change requires involved and costly legal processes could hamper adaptive management. The access provisions and their implementation will need to take account of potentially rapidly changing conditions and therefore should not hamper the need for equally rapid management responses.

If climate change potentially opens up opportunities to exploit new species or stocks, due to changes in their spatial distribution, then access rights will need to consider the existing exploitation on these species elsewhere. The overall sustainability of the stock and its new distribution will need to be considered in deciding whether to grant new access rights or give access to these new areas by existing rights holders. While there will be no historical precedent on which to base rights and allocations, an initial "line in the sand" can be drawn, and changes into the future could be via a stakeholder-led process. The intention would be to put the onus of responsibility onto the stakeholders. Any required changes to access rights or allocations would have to be proposed via a formal case addressing pre-defined criteria to provide justification for the proposed change. Ultimately access rights should take the triple bottom line into account, with economic, environmental and social objectives explicitly considered.

Range extending species can also give rise to cross sector allocation issues. For instance, if a range expanding species is particularly attractive to recreational fishers, when should commercial fishers be allowed access? Should species be allowed to establish first or can fisheries (recreational or otherwise) be permitted before populations of fish become established in a new region? Given that landings by recreational fisheries can match those from commercial fisheries for some inshore stocks it is safe to say that access to establishing stocks will remain a management challenge.

Decisions may also differ if the range expanding species are a considered a threat to the fundamental structuring mechanisms of an ecosystem, it may make sense to allow fisheries targeting them to act like a pest eradication program, preventing their effective establishment. However other species (such as some of the reef and demersal fishes) which may also cause disruption and transitory shifts in the ecosystem represent biodiversity turnover, replacing other species which can no longer maintain their role under the shifting environmental conditions. If the range extending species in that case was fished heavily to prevent its establishment then functional diversity and ecosystem function could be at risk in the long term. This means it will be necessary for managers (and the researchers supporting them) to act on a case-by-case basis, evaluating what role the new species will have in a future ecosystem.

Not all new fisheries will focus on range extending species. It is likely that other species will increase in abundance (or value). Developmental fisheries exist for a small number of invertebrates in Queensland, NSW, Victoria and South Australia (e.g. for sea cucumbers or jelly fish). While the future status of these specific fisheries is uncertain, allocation issues will still require attention.

Additional management issues that can limit adaptation to climate change

The action of regulators can also be an adaptation barrier. For example, if inertia or other processes prevent action this could induce synergistic effects from multiple stressors. While there is academic support for the proposition that more stringent management to reduce stress on ecosystems and give stocks more adaptive capacity (Hobday et al. 2007, Brander 2007), there is some ideological opposition to increased regulation. Moreover, the differential impacts and opportunities could also complicate adaptation by regulatory bodies. Individual adaptive capacity will influence the incentives of fishers and other stakeholders to comply with changing regulations (Fulton et al. 2011), as will perceptions of fairness (Gilligan and Richardson 2005).

Adaptation is easier if there is coherence industry wide rather than competition between individuals. Unfortunately, this unlikely to be the case for southeast Australia and so a more nuanced approach than any of the proposed strategies considered here will be required if effective, egalitarian and economically efficient management is to be assured (Eide and Heen 2002). As the existence of such an option is not guaranteed it is likely that adaption by regulatory bodies will need to navigate opposition from at least some sectors of society. Finally, governance changes will need to be ongoing, as the socioecological system (including features of Australian culture) will change through time, especially if regime shifts or other large scale changes occur.

Spatial management has been suggested as an alternative management method that is less reliant on reference levels, but does not perform well against all objectives, and has a range of potential barriers to adaptation. The current static form of spatial zoning used as the basis of conservation management is not well suited to the more fluid nature of future marine ecosystems. Shifting systems are likely to make some existing reserves less effective and others completely ineffectual (Hobday 2010). While this may lead to pressure to dissolve some protected areas and establish them elsewhere, rapid change is unlikely as acts of parliament are currently involved in the declaration of zones in Australia. Recognition of these limitations and the inappropriateness of static geographically defined zones for the conservation of highly mobile species means that future zones may be defined around oceanographic features rather than geographic coordinates (Hobday et al. 2011; Hobday et al 2014; Maxwell et al. 2015; Lewison et al. 2015; **Figure 6**).

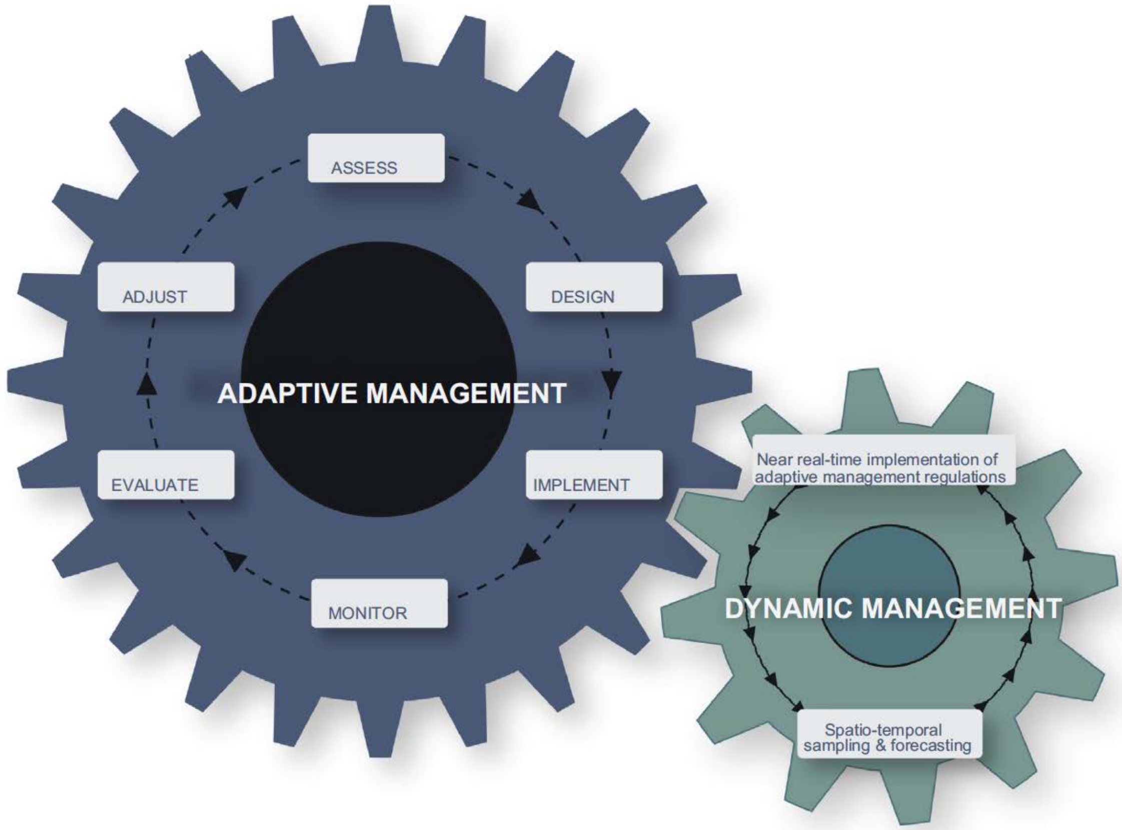

***Figure 6**. Dynamic ocean management can be integrated as part of adaptive management. Adaptive management is constructed of several steps including making value judgments about how marine resources will be managed. Dynamic ocean management couples into the adaptive management process by using spatio-temporal data to rapidly implement adaptive management protocols in near real-time as conditions change on-the-water. Source Maxwell et al. 2015.*

Coordinated management over large spatial areas and across sectors is an alternative management response that may provide improved adaptive capacity (as evidenced by the improvement in management performance when considering centralised or integrated management over fragmented management in the simulations). This broader scale, cooperative approach to management is already becoming a more common principal in Australian fisheries and coastal management (e.g. the proposals for a single management council for lobster in southern Australian states). As transition to fully integrated management has yet to happen, potential barriers to adaptation lie within what could be a long process of reshaping historical jurisdictional management. It may take some time for states to see the value in coordinated stock management, which would stymy effective adaptation (Productivity Commission 2012).

Some regulatory barriers to adaptation exist in the way that rules, put in place with the best of intentions in the context of historical ecosystems and fisheries, potentially inhibit adaptive behavioural changes – either by impeding individual risk management, inappropriately blunting price signals or limiting innovation by directly curtailing activities. For example, bycatch constraints (imposed to minimise the landings of species that were traditionally a marginal component of the system) could prevent effective targeting should abundance shifts out pace our regulatory processes. Barriers to the activity of companies across jurisdictions could impact cost efficiency and economic performance and, as discussed above, jurisdictional complications that are associated with range extensions.

Similarly, as described above, spatial zoning and spatially oriented access permits may constrain the ability of fishers to modify effort allocation in response to shifting species spatial distributions. Dynamic spatial zoning may be one option under a changing climate (Hobday et al. 2014; Lewison et al. 2015; Maxwell et al. 2015; **Figure 6**).

Attractive features of transferable licences may decline, for instance it is unlikely that new operators will buy in to a declining market, or alternatively quota may be hard to access if it becomes a means of supporting retirement incomes (van Putten and Gardner 2010). This is not to say that sound fisheries management practices be abandoned, but recognition that nimble management will be required. It is not yet clear what would be required for nimble management operating at maximum levels of sustainable harvesting rates. It is clear that good environmental information, transparently shared, facilitates good decision-making and is fundamental to the success of co-management more generally (Pomeroy et al. 2001). To date this is one key unifying factor in successful fisheries management approaches (Worm et al. 2009). If, however, effective and nimble management requires extensive monitoring or costly management interventions it may be beyond the management's resource base given the relatively small contribution of fisheries and aquaculture to Australia's GDP (AIMS 2010).

Modelling work for south eastern Australia has shown that the form of management used will be important for the adaptive capacity of Australian marine ecosystems, fisheries and aquaculture (Fulton and Gorton 2014). This is because one of the major barriers to adaptation could be management and regulations. The model analysis suggests that the current management approaches (fisheries and conservation) will be sufficient for at least some important species groups, such as large pelagic sharks, skates and rays and iconic mammals such as seals.

Timely management is needed in a changing environment

For many Australian fisheries, annual processes are in place for setting management measures such as quotas and effort controls. The adoption of harvest strategies in Commonwealth fisheries (e.g. Smith et al. 2014) and some state fisheries (e.g. Fletcher et al. 2016) formally link the management response to the assessment. However, because fisheries data has to be collected, synthesised and analysed, there is often up to two years between data collection and the management action. The implications of this in a rapidly changing environment need to be assessed.

If management action is not timely, simulation experiments to explore the implications of this when the system is transitioning to a new state or under a directional driver (as is the case with climate change driven environmental shifts in southeast Australia) were performed by Brown et al. (2012). They found that delays in management actions when a stock had static or declining productivity (e.g. due to environmental change) resulted in a greater probability of collapse (as a result of overfishing during periods with poor environmental conditions) and lower long-term stock biomasses regardless of the life history of the species (i.e. whether slow or fast growing, high or low productivity).

Brown et al. (2012) also found that fish catches varied less often through time with delays in the management system, but when change did occur it was often in much larger steps (to account for periods of overfishing in populations with declining productivity) ultimately ending with a 40% drop in harvest over 50 years. Thus delays in the assessment cycle provide a perception of stability in the short term, but in the long term a more responsive assessment system performs more strongly. They concluded that management delays should be minimized to promote long-term ecological and industry persistence. Alternatively conservative harvest limits are required to compensate for delays in management.

(g) the adequacy of current and proposed marine biodiversity protections given current and projected climate change impacts;

Key points

- Projected climate change and historical modification to marine systems means that biodiversity change is inevitable.
- Protected areas are one traditional management approach that also seems to support systems in resisting range invasions.
- Mobile protected areas, using dynamic ocean management as a pathway, may be one climate-ready solution for some species.

Information

We do not comment on the adequacy of Australia's commonwealth or state reserve networks per se, but note the evidence that protected areas seem to support systems in resisting range invasions under climate change.

Bates et al. (2013) showed that habitat reserves can promote ecological resilience to climate variability by supporting intact trophic webs and large bodied individuals. Specifically, in south-east Australia, reserve sites were distinguished from fished sites by displaying greater stability in some aspects of biodiversity, recovery of large-bodied temperate species, and resistance to colonization by subtropical vagrants. Likewise, Ling and Johnson (2012) evaluated the size-and shelter-specific survival of the range-extending long-spined sea urchin translocated to reefs inside and outside no-take Tasmanian marine reserves. They concluded that marine systems with a more natural complement of large and thus functional predators minimize local risk of phase shifts by reinstating size and habitat-specific predator-prey dynamics eroded by fishing. Finally, in tropical Australia, protected coral reefs recovered from bleaching and crown-of-thorns outbreaks more quickly.

Given, long periods of exploitation, observed and projected climate change, and the disappearance of some environments, Hobday (2011) suggests that a return to an original state is unlikely to be achievable in many systems. In addition, protection based on static marine protected areas is unlikely to meet common conservation objectives, as species and habitats are moving and species assemblages shuffling with the changing climate. Hobday (2011) advocated the use of mobile protected areas to afford protection to species' changing their distribution, and develop conservation objectives that are not underpinned by a return to historical baselines. This emerging area of dynamic ocean management is seen by some as a climate-proof protected area strategy (Hobday et al. 2014; Maxwell et al. 2015; Lewison et al. 2015), but will not be useful in all situations, particularly for benthic fauna.

Distributional shifts are not only challenging in the aggregate sense of conserving vulnerable species, but will raise social and industry challenges for management. Under the state-based jurisdictions currently in place for many coastal fisheries shifts in spatial distributions present multiple access, allocation and legal quandaries. While aquaculture will not have to grapple so much with shifting stocks it will face analogous issues around gaining access to suitable grow out locations (as environmental drivers shift and previously used locations become less suitable) given the already crowded nature of south eastern marine waters and the development of new industries, such as energy and aggregate mining.

Even more complicated jurisdictional and resource sharing issues arise when the spatial distribution across life histories becomes extended. The successful management of straddling stocks has been a topic of debate for many decades now (with the UN agreement on straddling and highly migratory fish stocks adopted in 1995), but has potential to become more of an issue within south-eastern waters in the coming decades. Differential mobility and physiological tolerances across life history stages means that shallow water species (e.g. some reef species) may end up relying on a small number of productive "source" spawning locations supporting the exploited populations in locations downstream, which could be in different states or jurisdictional areas to the spawning sites. This raises thorny questions about relative responsibility and benefit and how to effectively recompense fishers surrounding the source populations – areas which might be reserved for the benefit of downstream users.

(h) the adequacy of biosecurity measures and monitoring systems given current and projected climate change impacts;

Key points

- Many of the issues associated with biosecurity were addressed under TOR (c).
- Current biosecurity measures, if sufficiently resourced, are also likely to be adequate under climate change.
- Australia is guided by a series of national and international guidelines. These may need to be revisited in light of climate change.
- Enhanced monitoring may be required, particularly as undesirable species and diseases may occur in new places around Australia due to a changing environment.

Information

Many of the issues associated with biosecurity were addressed under TOR (c), and we make only several additional points.

Marine biosecurity is focused on preventing the arrival of unwanted species. Many species have arrived in Australian waters attached to the hulls of vessels of all types from yachts to commercial ships, or in their ballast water. Others have been introduced to support local aquaculture, with the aquarium industry another vector. We consider here the ballast water issue, as this is most likely to be affected by climate change. Current measures, if sufficiently resourced, are also likely to be adequate under climate change. New source areas may need to be considered, as Australia's marine climate changes. Enhanced monitoring may be required, particularly as undesirable species and diseases may occur in new places around Australia due to a changing environment.

The difficulty and expense of eradicating introduced marine species has focused national management efforts on reducing initial introductions to Australia, early detection of introductions and limiting the spread of species once established.

The black-striped mussel outbreak in Darwin in 1999 highlighted the need for an integrated approach to managing marine pest incursions in Australia. A national taskforce recommended the establishment of the National System for the Prevention and Management of Marine Pest Incursions. The national system established in 2005, focuses on the prevention, emergency preparedness and response, and ongoing management and control of marine pests. Emergency response elements are governed by the National Environmental Biosecurity Response Agreement. Components of the National System, which include guidelines and information on monitoring, biofouling and ballast water and continue to be implemented under the guidance of the Marine Pest Sectoral Committee – a national technical and advisory committee made up of representatives from the Australian, state and Northern Territory Governments. The national system applies the biosecurity principles and framework outlined in the Intergovernmental Agreement on Biosecurity (IGAB) for the marine pest sector. The IGAB came into effect in 2012. It aims to strengthen the working partnership between governments and to improve the national biosecurity system and minimise the impact of pests and diseases on Australia's economy, environment and the community.

In the event of a marine pest incursion of national significance, the Consultative Committee on Introduced Marine Pest Emergencies would be convened. This national technical forum, consisting of members from the Australian, state and Northern Territory Governments, would provide advice on the feasibility and coordination of a national response as per the Emergency Marine Pest Plan (see www.marinepests.gov.au/national-system/how-it-works/Emergency_management/)

A recently concluded review of Australian Government policy on introduced species, together with implementation of the new *Biosecurity Act 2015*, should provide an improved and more nationally consistent approach to domestic policy and legislation. The International Maritime Organisation, in consultation with member states, has developed two sets of international guidelines addressing introduced species. The first, the *International guidelines for preventing the introduction of unwanted aquatic organisms and pathogens from ships' ballast water and sediment discharges*, was adopted by the Marine Environment Protection Committee in 1991 and the second, the *International guidelines for the control and management of ships' biofouling to minimize the transfer of invasive aquatic species*, was adopted by the committee in 2011. Although adherence to the guidelines is voluntary, they provide a basis upon which to further promote a best-practice approach to ballast water and biofouling management for the prevention of introduced species incursions.

The *International guidelines for preventing the introduction of unwanted aquatic organisms and pathogens from ships' ballast water and sediment discharges* was further developed into a resolution adopted by the International Maritime Organisation Assembly in 1997 and then the International Convention on the Control and Management of Ships' Ballast Water and Sediments in 2004. Because of a range of concerns about technical feasibility and efficacy of the available technology, the 2004 Convention is yet to enter into force. The required entry into force criteria (ratification by 30 states, representing 35% of world tonnage) is likely to be met in 2016, which means that the convention will enter into force in 2017. Following entry into force, all vessels will need to fit a ballast water management system by their first MARPOL Annex I (IOPP) renewal survey. This will have a significant impact on the environmental performance of international shipping with respect to the ongoing translocation of species around the globe and around the Australian coast.

Under climate change, the source populations from overseas may change, as our climate becomes more similar to other regions not currently considered a risk. Thus, continually updating the potential source locations that match our changing ocean and coastal environment may be required.

(i) any other related matters.

We make the further comments on three additional areas, and outline these in detail below. These are:

1. Research priorities for fisheries and aquaculture under climate change: We note that there has also been efforts led by the National Climate Change Adaptation Research Facility to determine the priority research questions for fisheries and aquaculture. CSIRO staff have contributed to this effort.
2. Precautionary approaches to the future may be needed under climate change.
3. Modification of the environment as an adaptation to climate change.

Priority research questions identified by the National Climate Change Adaptation Research Plan – Marine Biodiversity and Resources

Key Points

- Priority research questions for fisheries and aquaculture have been identified by a national writing and review team as part of activity directed by the National Climate Change Adaptation Research Facility.
- Priority questions are focused on improving the policy and governance that supports adaptation to climate change in fisheries and aquaculture.
- There is no funding allocated to addressing these priority research questions at this time.

Information

The National Climate Change Adaptation Research Facility (NCCARF) was established by the Australian Government in 2007 (and then further funded from 2014 to 2017) to coordinate and lead the Australian research community in generating the biophysical, social and economic information and tools needed to facilitate adaptation to climate change. A key role of NCCARF is to coordinate the development of the National Climate Change Adaptation Research Plans (NARPs) across a range of priority areas.

National Writing Teams have recently drafted National Adaptation Research Plans for 2016. The NARP Marine Biodiversity and Resources team reviewed the previous NARPs (2010 and the update in 2012) and identified research priorities and changes given the progress in knowledge and research since the date of the last NARP. This document is now out for review.

That document updates their review, by quantifying the coverage of questions over the period 2009-2015, and qualitatively describing the literature published since the last review (including literature published in 2016). The literature review is structured in a manner that reports against the research questions that were updated in Holbrook and Johnson (2012). Based on the total body of published literature since January 2009 and projects completed, priority questions have been identified four sectoral theme areas and a fifth cross-cutting theme. These themes are:

- Aquaculture;
- Commercial and recreational fishing;
- Conservation management;
- Tourism and non-extractive recreational uses; and
- Cross-cutting issues.

The priority research questions for Aquaculture and Commercial and Recreational fishing are provided below. Indigenous fishing is covered in another NCCARF plan.

Aquaculture

New Priority Questions	Category of Q
2.1 What are the most likely effects of climate change on key environmental variables affecting aquaculture operations (including ocean temperature, stratification and oxygenation, freshwater runoff or availability, and extreme wind and wave events), and which regions are most vulnerable to such changes?	Impact
2.2 How can aquaculture businesses adapt to climate change effects either by minimising adverse impacts or taking advantage of opportunities?	Adaptation
2.3 What are the key aquaculture policy issues that need to be addressed to enable adaptation to climate change? How will aquaculture be affected by future climate adaptation policies in other sectors, such as fisheries, coastal land use planning and water management?	Policy & governance

Fisheries

New Priority Questions	Category of Q
3.1 What options or opportunities are there for commercial fishers in identified vulnerable fisheries to adapt to climate change effects through changing target species, capture methods and management regime, risk management, or industry diversification, relocation or divestment?	Adaptation
3.2. What are the key fisheries policy issues that need to be addressed to enable adaptation to climate change (e.g. dealing with fixed fishery zones when the stock distribution is changing and development of harvest strategies that are robust to climate change effects)?	Policy & governance
3.3 How will fisheries policy be affected by future mitigation and adaptation policies in other sectors, such as no-harvest conservation measures?	Policy & governance
3.4 How have enablers to adaptation been used and barriers to adaptation overcome? What significant changes in fisheries have occurred before because of extrinsic factors and what can be learned from those changes that will inform adaptation to climate change?	Policy & governance

There is no funding allocated to addressing these priority research questions at this time.

Precautionary approaches to the future may be needed under climate change

Key points

- The future is not known – fisheries and aquaculture managers will need to remain flexible and adaptable.
- Management approaches should be more dynamic and respond to changes in the systems.

Information

Perhaps the greatest challenge facing managers of Australian fisheries and aquaculture is that they do not know how the global human population will respond in the coming decades and so what emissions will actually be. Given the differing degrees of system change seen under the different emissions scenarios it is clear that strategic decisions and investments would be very different if managers knew beforehand which trajectory they were on. Unfortunately, that will never be the case so managers will need to remain flexible and adaptable if they are to successfully negotiate such an uncertain future. In essence this is no different to the premise behind adaptive management or the evolving idea of governance based on resilience thinking. Nevertheless it is more complicated (and challenging) as it must be accomplished against a background of non-stationary system drivers.

Resource management still largely depends on an equilibrium approach – comprehensive, adequate and representative reserves that are fixed in space, and fisheries using fixed reference points in assessments. While new management methods may be found in the coming decades, for now the way forward appears to be by modifying well-accepted management procedures so that they are more non-stationary – such as allowing for regime shifts in stock assessments, allowing for non-stationarity in management strategies, or using dynamic forms of once stationary management levers, such as fisheries closures based on water bodies rather than a fixed geographic location. General concepts of how such modifications could be made will be the most useful information to share as system idiosyncrasies will mean universal solutions will likely not exist.

Modification of the environment as an adaptation to climate change

Key points

- Modification of the environment to reduce the impacts of climate change may be an approach that can help fisheries cope.
- The success of such approaches would be dependent on coordination across sectors and levels of government and needs a strategic approach.

Information

Modification of the environment to tailor it to human needs is a feature of marine ecosystem use in some nations (e.g. use of artificial reefs and structures in ocean ranching in Japan and China). Such direct intervention to address short falls in life history strategies could alleviate any stage failures through restocking programs or the hatchery rearing of critical life history stages that can no longer successfully survive or arrive in the traditional locations. Such approaches have been used (e.g. in salmon fisheries) to address stock depletion due to habitat loss or overfishing, though have seen less use in marine systems. One Australian example is the translocation of lobsters in Tasmania to improve growth and attractiveness as a fishery resource (Chandrapavan et al. 2010; Green et al. 2010). Calls for these interventions may become more common in future under climate change, and represent an attempt to overcome some of the challenges imposed.

Such interventionist approaches may be subject to some level of social dissonance and conservation concern (Hobday et al. 2014) and so broader community based debate and consultation would be appropriate. Even if direct life history intervention is considered too extreme, other system modifications in support of increasing adaptive capacity may be found to be acceptable (e.g. the protection of estuarine nursery habitats, or the modification of flow regimes to enhance fecundity or migration success). The success of such approaches would be dependent on coordination across sectors and levels of government, as built infrastructure may prevent the retreat of crucial habitats; actions by one industry may undermine another; and competition between industries may constrain access to fishing grounds (or aquaculture habitat), ports and freight services.

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