Fisheries New Zealand
Tini a Tangaroa

Assessment of potential effects of climate-related changes in coastal and offshore waters on New Zealand's seafood sector

New Zealand Aquatic Environment and Biodiversity Report No. 261

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EXECUTIVE SUMMARY

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Measurable environmental changes are already occurring in New Zealand waters. Warming sea temperatures and ocean acidification are but two of the changes observed to date, and such changes are known to have implications for the seafood sector (i.e., aquaculture and wild-caught fisheries).

Risks and opportunities are likely to arise for the seafood sector as a consequence of climate and ocean change effects in coastal and offshore New Zealand waters. This study, conducted in stages over four years, synthesises available information on CO_2 and climate-induced changes that affect the New Zealand region and our fisheries. It summarises the known implications of these changes to the physical and oceanographic system in the coming decades, and knowledge of how specific fisheries are influenced by these parameters; this information is combined to determine potential risks to these fisheries.

The state of knowledge of climate and ocean change-associated predictions for components of New Zealand's marine environment that are most relevant to fisheries are presented. Past and future projected changes in coastal and ocean properties, including temperature, salinity, stratification and water masses, circulation, oxygen, ocean productivity, detrital flux, ocean acidification, coastal erosion and sediment loading, and wind and waves, are reviewed. Responses to environmental change for these coastal and ocean properties are discussed. Their likely impact on the fisheries sector, where known, is presented.

A <u>complete</u> understanding of the response of key New Zealand fisheries species to climate-associated change, based on scientific data, is ambitious given the paucity of information on the majority of these species, the ecosystems that support them, and the potential threats they face. This study reviewed the biological and ecological characteristics of 32 commercial fisheries species or species groups important in the New Zealand region, and evaluated how they might be affected by changes to selected properties of New Zealand's oceanic and coastal waters expected over the remainder of this century. Regardless of the data limitations, the study identified a number of species that may be affected by warming, and/or ocean acidification, supporting previous findings that these are the two greatest anthropogenic CO_2- associated threats facing the New Zealand marine environment.

A range of decision support tools in use in assessing global change risks overseas were evaluated with respect to their applicability for dissemination of the state of knowledge on anticipated environmental changes and fisheries. Three species, for which there was a relatively large amount of information available, were chosen from the main fisheries sectors for further analysis. These were pāua, snapper, and hoki (shellfish, inshore, and middle-depths/deepwater fisheries, respectively). Evaluations of each species' sensitivity and exposure to climate change-associated threats, based on currently available published literature and expert opinion, assessed vulnerability to future projected environmental change of pāua as 'very high', of snapper as 'moderate', and of 'hoki' as 'low'. Potential adaptation and management options, and their effectiveness and feasibility, were also examined.

This project has summarised a large amount of multidisciplinary information, always with the fishery and effective management in a changing environment in mind. It has demonstrated the value of research into direct influences of the different parameters on the species (e.g., temperature, acidification), and the need for understanding across the life cycle of the species to enable robust evaluations and predictions of future impacts to be made.

1. INTRODUCTION

New Zealand's coastal and oceanic waters support a valuable seafood sector, contributing significantly to the country's annual economy (Ministry for the Environment & Stats NZ 2019). Measurable climate change effects are already happening in New Zealand waters. Warming sea temperatures and ocean acidification are but two of the changes observed to date, and such changes are known to have implications for the seafood sector (i.e., aquaculture and wild-caught fisheries).

New Zealand waters have already begun to experience changes in key ecosystem parameters associated with climate change (Lundquist et al. 2011; Reisinger et al. 2014; Pinkerton 2017; Law et al. 2018b; Pinkerton et al. 2019; Sutton & Bowen 2019). Most pertinent amongst these are the well documented warming and acidification of the global oceans due to increased atmospheric CO_2 concentrations – changes that are occurring at rates unprecedented on historical time scales (IPCC AR5 2013; IPCC 2019). The knock-on effects of climate change on other potential stressors in coasts and oceans are also well recognised; for example, there will be more frequent input of freshwater and sediments to coastal regions due to changes in frequency and intensity of rainfall and storm events (Mullan et al. 2011; Reisinger et al. 2014). In combination, these stressors will likely alter the functioning of marine ecosystems (e.g., Hofmann et al. 2010; Hurst et al. 2012), through their influence on habitats, food webs, and species interactions (for example). However, the implications of these complex and interactive changes to the future productivity of New Zealand's seafood sector require further research – particularly around the relative risks to each fishery-type, and to specific species, e.g., what is known already and what are the knowledge gaps? (Lawler et al. 2010; Diamond et al. 2013; Howard et al. 2013; Pecl et al. 2014).

Seafood sector stakeholders frequently ask about the ramifications and timelines of climate change effects on the ocean. The vulnerability of the seafood sector to anthropogenically induced environmental change is a concern globally (Lam et al. 2016; Savo et al. 2017; Blanchet et al. 2019), particularly the impacts on fisheries (shifts in distributions and abundance) and the communities they support (Morrison et al. 2015; Hare et al. 2016). For example, internationally (and particularly in the USA), aquaculture and wild-caught shellfish industries have become far more alert to the threat of ocean acidification (e.g., Cooley et al. 2012; Capson & Guinotte 2014). This sector is also grappling with the effects of acidification and warming combined with changes in other stressors (e.g., sedimentation, increased prevalence or spread of disease, water quality). Questions are being asked about: the likely key life history bottlenecks and physiological impacts; the stressors and combinations of stressors most likely to cause impact; the regions that will be most affected; and to what extent mitigation is possible from a management perspective. Projections for change in coastal regions are particularly difficult – global ocean models often have limited relevance when downscaled to coastal regions, where there is already considerable variation due to the influence of tides and interactions between changes in rainfall and land-use that affect sediment supply from the terrestrial system.

This report aims to ***identify risks that are likely to arise for the seafood sector as a consequence of climate change effects in coastal and offshore New Zealand waters***, through the synthesis of available information on CO_2 and climate-induced changes that may affect these regions and their fisheries. Changes to the physical and oceanographic system are described along with the state of knowledge of how specific fisheries are influenced by these parameters and used to determine potential risks to these fisheries.

Using data and projections sourced both from New Zealand and globally, this report (Specific Objective 1) describes the changes taking place in New Zealand waters including sources of data and reporting of trends in New Zealand and key predictions and uncertainty of projection scenarios. The report also provides an evaluation of how climate change might influence 32 of New Zealand's commercial fisheries. Essentially, the report provides a literature-supported description of the current *state of knowledge* and understanding of future changes in key parameters influencing New Zealand fisheries.

This report will provide a reference document for marine management professionals, describing which factors should be considered when identifying and implementing adaptation options in their particular seafood sectors. The objectives of the project align with issues highlighted in a recent report summarising the key challenges for New Zealand's oceans (Ministry for the Environment & Stats NZ 2019) and issues raised by the Parliamentary Commissioner for the Environment in a summary of environmental reporting (Parliamentary Commissioner for the Environment 2019). The information gathered and used in this project underpins the ecosystem-based management approach, is aligned with the aims and research proposed in the Sustainable Seas National Science Challenge (https://sustainableseaschallenge.co.nz/), and builds on the oceans case study in the MBIE-funded 'Climate Change Impacts and Implications' project (Law et al. 2016; Law et al. 2018b; https://ccii.org.nz/l).

The report is divided into four main sections:

'A changing marine environment – observations and projections' provides a summary of the state of knowledge of key environmental parameters that influence New Zealand's coastal and oceanic marine environment (and that potentially affect fisheries). This section summarises how key parameters have changed to date, and how they may change in the future. The primary parameters of interest detailed by this report include ocean properties (water temperature, salinity, stratification and water masses, wind and waves, currents and circulation, oxygen, productivity, detrital flux), ocean acidification, and coastal erosion and sediments.

'Evaluating New Zealand fisheries' summarises the state of knowledge of selected key New Zealand fisheries species – their habitat type, distribution (including with respect to temperature and depth), stock structure, reproduction, recruitment, growth, and diet. This knowledge is important for determining how a species may be influenced by changes in the marine environment.

'Evaluating effects of environmental change on New Zealand fish stocks' summarises available species-specific information to comment on potential climate and ocean change impacts, including from a perspective useful for quantitative fisheries assessments (stock assessment parameters). It also briefly describes a preliminary investigation of the use of a statistical spatial population model and remote sensed environmental data to estimate fish distribution under climate change.

'Tools for evaluating risks to fish stocks and fishery adaptation options' summarises the output of a series of stakeholder workshops, attended by industry partners, scientists and fisheries managers, to explore current and future understanding as well as gaps in knowledge of climate change impacts. Three species were selected as examples to demonstrate the process of performing detailed climate and ocean change risk assessments: pāua, snapper, and hoki (examples from shellfish, inshore, and middle depths/deepwater fisheries, respectively).

2. A CHANGING MARINE ENVIRONMENT — OBSERVATIONS AND PROJECTIONS

New Zealand waters extend from the subtropical waters of the southwest Pacific Ocean (at 26° S) to the Subantarctic waters (at 56° S). This marine estate (territorial waters, exclusive economic zone (EEZ), and extended legal continental shelf claim area) covers 5.9 million km^2 (Figure 1). Continental shelf waters (shallower than 250 m depth) can extend from the coastline to as little as 1 km offshore (e.g., Milford Sound) or to more than 100 km offshore (e.g., off Taranaki). Ocean waters include deep abyssal plains, deep-sea trenches, extensive submarine ridge and plateau systems, and seamounts (MacDiarmid et al. 2013).

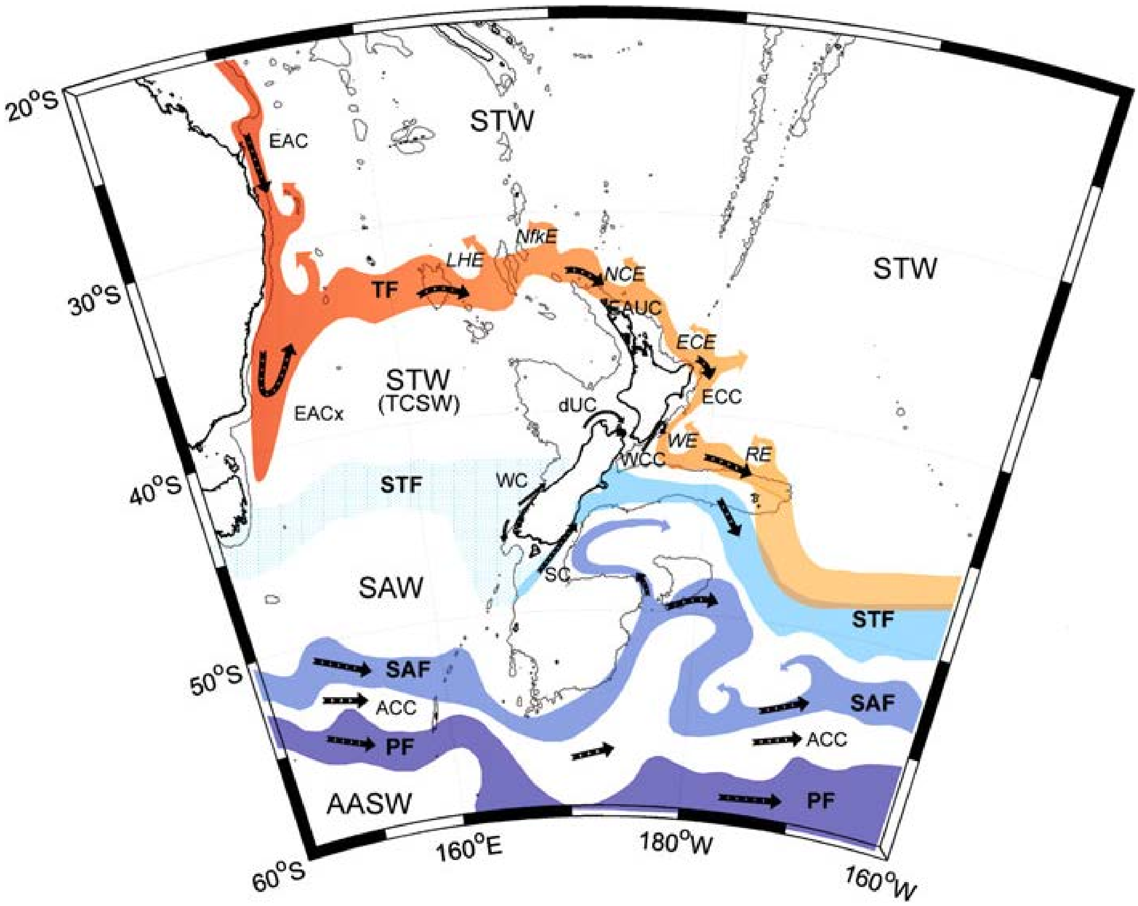


Figure 1: Main oceanographic features of New Zealand. Regions of flow are shown as coloured streams. Colours reflect the temperature of the flows, with red being warmest and dark blue being coldest. The Subtropical Front (STF) in the Tasman Sea is density compensated with little flow, as indicated by the shading. Water masses are Subtropical Water (STW), Tasman Sea Central Water (TSCW), Subantarctic Water (SAW), and Antarctic Surface Water (AASW). Ocean fronts are Tasman Front (TF), Subtropical Front (STF), Subantarctic Front (SAF), and Polar Front (PF). Ocean currents are East Australia Current (EAC), East Australia Current extension (EACx), East Auckland Current (EAUC), East Cape Current (ECC), d'Urville Current (dUC), Wairarapa Coastal Current (WCC), Westland Current (WC), Southland Current (SC), and Antarctic Circumpolar Current (ACC). Eddies are Lord Howe Eddy (LHE), Norfolk Eddy (NfkE), North Cape Eddy (NCE), East Cape Eddy (ECE), Wairarapa Eddy (WE), and Rekohu Eddy (RE). (Figure reproduced from Chiswell et al. 2015, with permission.)

New Zealand's location in the Southwest Pacific Ocean places it at the junction of a number of oceanographic regimes. In the north, waters are influenced by the South Pacific Gyre and eddies that have spun off the East Australian Current to form the Tasman Front. This combination of influences makes the north and north east of North Island heavily dominated by water masses of sub-tropical origin. These water masses also influence the Tasman Sea, as far south as the Subtropical Front (STF). The Subtropical Front crosses the Tasman Sea at 45–50° S, approximately the latitude of Fiordland, before dipping south of the South Island and following the continental shelf break up the east coast of the South Island and turning east along the crest of Chatham Rise. South of New Zealand, the oceans are dominated by the Southern Ocean and, in particular, by changes to the Antarctic Circumpolar Current (ACC) (Chiswell et al. 2015).

New Zealand climate is strongly influenced by three large-scale climate cycles: (1) the El Niño-Southern Oscillation (ENSO) quasi 4 year cycle of the tropical Pacific, often described by the Southern Oscillation Index (SOI); (2) the longer-term (20–30 year) Interdecadal Pacific Oscillation (IPO); and (3) the Southern Annular Mode (SAM) [also called the High Latitude Mode or Antarctic Oscillation (AAO)] (Salinger & Mullan 1999; Salinger et al. 2001; Bhaskaran & Mullan 2003; Kidson et al. 2009).

Climate change is a well-documented global phenomenon that is impacting the marine environment, and in particular the Southern Ocean (Roemmich et al. 2015; Llovel & Terray 2016; Sallée 2018). Warming of the climate system since the 1950s is unequivocal, with many of the observed changes unprecedented over time scales of decades to millennia (IPCC 2014). Although average changes may have been small to date, a shift in average climate conditions can significantly affect the frequency at which extreme events (those above a set threshold) can occur (Hobday et al. 2016). In the fifth assessment report (AR5) of the Intergovernmental Panel on Climate Change (IPCC), Chapter 3, Rhein et al. (2013) summarised research on changes in the global ocean and found strong evidence that ocean properties have changed significantly during the past 40 years (including temperature, salinity, carbon, pH, and oxygen). Trajectories of change measured in New Zealand's oceans follow these global trends (Gluckman 2013; Rouse et al. 2017; Law et al. 2018b; Shears & Bowen 2017; Pinkerton et al. 2019; Sutton & Bowen 2019).

With respect to expected changes, Earth System Models can provide projections of the different stressors that marine systems may experience as a result of climate change (Boyd et al. 2015). Earth System Models are large scale models which can be used as a framework to examine changes in carbon input and the implications of these to various components of the ocean system. Projections of future changes around New Zealand come from IPCC Climate Model Intercomparison Project 5 (CMIP5) Earth System Models (Taylor et al. 2012). As Earth System Models are not developed specifically for a particular region, validation is required to determine which model, or subset of models, perform best for the region of interest. For example, an assessment of the utility of 16 different CMIP5 biogeochemical models for the New Zealand region was undertaken by Rickard et al. (2016), to determine the best subset of models for future projections (see text box below for more information). From the ensemble of 16 models, a subset which performed best for the New Zealand region was identified.

Future Projections using IPCC Representative Concentration Pathways

This section refers to projections of change made using Representative Concentration Pathways (RCPs, IPCC AR5 2013). These are scenarios based on the possible trajectories for continued emissions of greenhouse gases (including CO_2). These RCPs have been used as input for climate models, including some of the future ocean modelling research reviewed by this report.

The four RCPs are:

RCP2.6 represents an emissions pathway where a peak in radiative forcing eventually leads to low concentration levels of greenhouse gases (van Vuuren et al. 2007). In order to reach these low levels, greenhouse gas emissions (and, indirectly, emissions of air pollutants) are reduced substantially over time using negative emissions technology.
RCP4.5 represents a stabilisation scenario where total radiative forcing is stabilised before 2100 by employment of a range of technologies and strategies for reducing greenhouse gas emissions (Clarke et al. 2007).
RCP6.0 represents a stabilisation scenario where total radiative forcing is stabilised after 2100 without overshoot by employment of a range of technologies and strategies for reducing greenhouse gas emissions (Hijioka et al. 2008).
RCP8.5 represents a "worst case' emissions scenario characterised by increasing greenhouse gas emissions over time, and high greenhouse gas concentration levels. (Riahi et al. 2007).

Currently, CO_2 emissions are tracking RCP8.5.

The observed changes in New Zealand's coastal and ocean properties to date, and changes expected in these properties in the future, are described below. The primary parameters of interest include water temperature, salinity, stratification and masses, circulation, oxygen, coastal erosion and sedimentation, and ocean acidification. Information on primary productivity and waves is also briefly discussed.

2.1 Temperature

Key findings:

- Coastal and ocean sea surface temperatures have warmed around New Zealand between 1981 and 2018. The average annual rate of sea surface temperature warming for the New Zealand EEZ was 0.016 °C per year.
- Anomalously high sea surface temperature warming was noted in the 2017–2018 and 2018–2019 summers (summer 'heatwaves').
- Sea surface temperature warming of 2.5–3.0 °C is projected by 2100 around most of New Zealand, with the largest warming anomalies (over 3 °C) in the Tasman Sea and Subantarctic water south of the Chatham Rise.

(i) Temperature measurements available for the New Zealand region

Observations of ocean temperature were infrequent and sparse until satellite measurement of sea surface temperature (SST) began in 1981. The Advanced Very High Resolution Radiometer (AVHRR) series, operated by NOAA (National Oceanic and Atmospheric Administration of the USA), began in October 1981 and continues to the present. Processing and analysis methods reconcile multiple sensors and interpolate across areas and times where data are missing due to cloud cover (Reynolds et al. 2002).

For subsurface temperature, the first regional routine measurements are from regular deployments of free-falling temperature measuring probes (known as expendable bathythermographs, XBTs) deployed from commercial ships along two transects with endpoints in New Zealand. An Auckland-Suva line started in 1986 and a Sydney-Wellington line began in 1991. These transects are usually sampled four times per year and provide data from the upper 800 m of the ocean along the tracks between ports. Many research vessel transects were previously collected as part of the World Ocean Circulation Experiment in the 1980s and early 1990s, but only a subset of these continue to be repeated. There are two other transects that have been repeated irregularly in the greater New Zealand region: one across the Southern Ocean south of Tasmania, and the other along 170° W to the east of New Zealand. There is also an international archive of historical transects, from which changes have been observed.

Routine broad scale observations began with the deployment of Argo profiling floats in 2000. These floats have provided a significant step change in observing the global ocean. Drifting at 1000 m depth, and profiling between 2000 m and the surface every 10 days, with the initial designed global array density achieved in 2006 (i.e., one float in every 3 degrees of latitude/longitude area of the ocean deeper than 2000 m), they provide well-distributed observations across the global ocean (see www.argo.net). Sampling of the deep ocean below 2000 m is still largely limited to full depth oceanographic surveys carried out by research vessels, but a new global programme using floats that profile to 6000 m (Deep Argo, Johnson et al. 2015) is under development.

(ii) Observed temperature changes

Globally, zonally-averaged (i.e., averaged over longitude) upper ocean temperature trends show warming at nearly all latitudes and depths (Levitus et al. 2009). There is a clear warming trend of sea surface temperature in the Southern Hemisphere, where 71% of the variance in temperature can be explained by a linear warming trend. If the South Pacific Ocean is considered in isolation, however, only 27% of the variance is explained by a linear warming trend, meaning that the linear warming component accounts for less of the variability in the time series. Around New Zealand, satellite data since 1981 show that different areas exhibit different patterns of surface warming (Pinkerton et al. 2019), highlighting the fact that there are complex, regionally-specific patterns of variability in addition to a gradual increase. There is also evidence of subsurface warming, with a reported warming of 1.2 °C in the upper 800 m of ocean occurring between 1996 and 2002 in the Tasman Sea (Sutton et al. 2005). Highest regional warming is apparent south of 30° S (Gille 2008; Levitus et al. 2009; Sutton & Bowen 2019; Figure 2). The magnitude of warming varies among studies, likely due to biases in sampling resulting from different time series lengths as well as different methods of interpolating observations across poorly-sampled regions in the Southern Hemisphere.

South of the Subantarctic Front (Figure 1) much of the water column warmed between 1992 and 2005, apparently at a faster rate than the upper-ocean global mean (Gille 2008; Purkey &s Johnson 2010). Below 4000 m there has been statistically significant warming east of New Zealand, which has been linked to warming in the Southern Ocean (Purkey & Johnson 2010). The same study identified no warming below 4000 m north of New Zealand, and although warming below 4000 m was found in the Tasman Sea basin, it was not a statistically significant trend.

El Niño has also been identified as having a strong influence on ocean heat uptake (cooling; e.g., Sutton & Roemmich 2001; Bowen et al. 2017; Sutton & Bowen 2019) with inter-annual vertical redistribution of ocean heat between the upper ocean and mid depths occurring at approximately eight times the rate of multi-decadal warming (Roemmich & Gilson 2011).

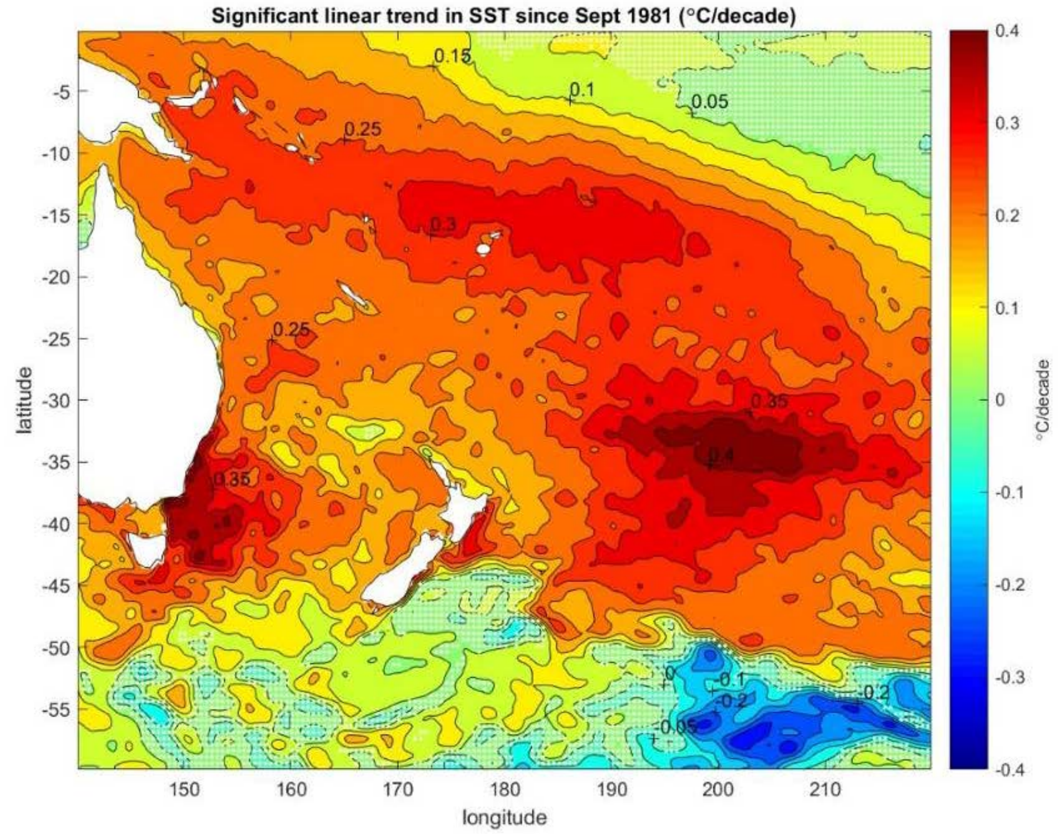


Figure 2: The linear trend in SST 1981–2017 calculated from the NOAA OI SST V2 High Resolution Dataset (Banzon et al. 2016; Reynolds et al. 2007). Contour intervals are 0.05 °C/decade. (Figure modified from Sutton & Bowen 2019.)

Based on satellite observations of sea surface temperature (SST) alone, most of the New Zealand region has experienced warming of the surface ocean between 1981 and 2018 (Shears & Bowen 2017; Pinkerton et al. 2019; Sutton & Bowen 2019). The average annual rate of SST warming (using the method of Sen 1968), based on monthly SST anomalies for the New Zealand EEZ, was 0.016 °C per year which is very close to the global average between 1981 and 2018 of 0.012 °C per year (Pinkerton et al. 2019). The magnitudes of the trends and levels of significance depend very much on the period of analysis, because of the presence of long-term cycles and autocorrelation in the SST time series.

During the 2017–2018 summer, parts of the New Zealand region experienced a period of anomalously high warming that resulted in a SST anomaly of +4 °C in parts of the eastern Tasman Sea and Subantarctic water south of the Chatham Rise in December (Pinkerton 2018; Pinkerton et al. 2019; Salinger et al. 2019). Another summer heatwave occurred in 2018–2019, with record breaking air temperatures detected (NIWA summer 2018-19 climate summary, NIWA 2019). These marine heat waves were shallow, surface-intensified events affecting the upper 20–40 m of the water column (Salinger et al. 2019). An MBIE Endeavour project, initiated in 2019, will develop oceanographic forecasting tools to predict when these marine heat waves will occur (https://www.moanaproject.org/).

(iii) Projected temperature changes

Rickard et al. (2016) reported the mean expected temperature changes for 2100, calculated using a suite of Earth System Models both regionally (Figure 3) and for the whole of the New Zealand region. The inner Earth System Model ensemble indicates that, under the RCP8.5 scenario, SST around New Zealand will increase on average by 2.5 °C (1.6–3.3 °C) by 2100. Under RCP4.5, SST will increase by 1.15 °C on average (range 0.55–1.7 °C) (Law et al. 2018b). Predicted changes in New Zealand subregions 1 to 6 all had the same sign as the mean changes predicted for the whole of New Zealand, with a projected warming of 2.5–3.0 °C. Subregion 7 (Subantarctic, south of 46° S) had lower projected warming (about 1.5 °C). Further analysis using only the two best Earth System Models (Law et al. 2018b), highlighted regional variation in projected warming: the Tasman Sea and Subantarctic water south of the Chatham Rise exhibited the largest warming anomaly by 2100, of over 3 °C, with the lowest warming in Subantarctic water south of 55° S.

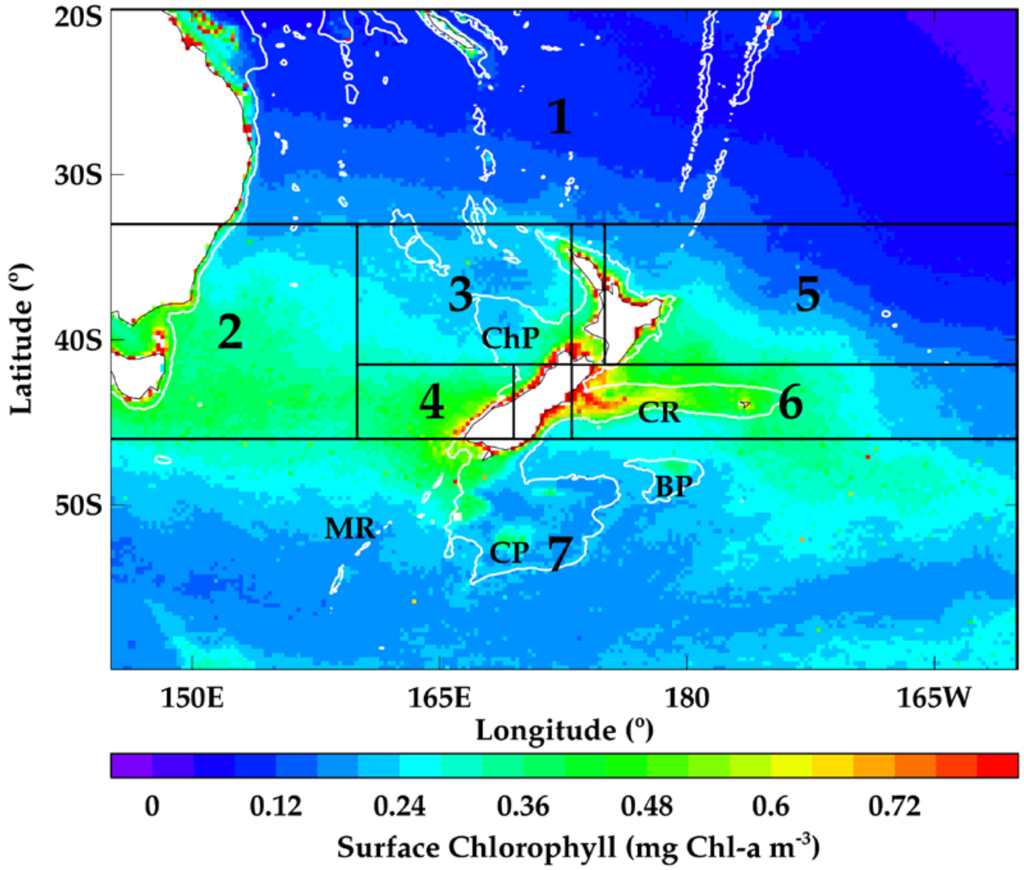


Figure 3: The seven subregions used in Earth System Model projections of change in temperature around New Zealand (labeled 1–7). White contours show the GEBCO 1000 m isobath. Labeled submarine features are BP (Bounty Plateau), CP (Campbell Plateau), ChP (Challenger Plateau), CR (Chatham Rise), and MR (Macquarie Ridge). The colour indicates mean surface chlorophyll (mg Chl-a m^{-3}) over the southwest Pacific Ocean, derived from SeaWiFS satellite. (Figure modified from Rickard et al. 2016.)

2.2 Salinity

Key findings:

- Surface waters around New Zealand have become saltier (Tasman Sea and over the Chatham Rise), whereas east of northern and southern New Zealand they have freshened.
- The intermediate layer (average depth about 700 m) has freshened, particularly in the Southern Ocean, and in water masses such as the Antarctic Intermediate Water and Subantarctic Mode Water.
- Localised surface freshening in coastal areas with increasing rainfall and run off (e.g., Fiordland).

Changes in ocean salinity, as with temperature, affect ocean circulation and stratification through impacts on seawater density. The horizontal salinity distribution of the upper ocean largely reflects the exchange of freshwater with the atmosphere, with high surface salinity found in regions where evaporation exceeds precipitation, and low salinity in areas of excess precipitation and runoff. Salinity is also modified by ocean currents transporting water with different characteristics.

Observations of salinity in the ocean prior to the development and deployment of Argo floats were only made along hydrographic transects, so were generally sparse and infrequent. Globally, sea surface salinity change has been found to be correlated with present salinity anomalies; that is, salty places have been getting saltier and fresh places getting fresher for the past 30 years (Hosoda et al. 2009). This pattern is consistent with the hydrological cycle accelerating, which is in turn consistent with predictions from global models.

(i) Observed salinity changes

Around New Zealand salinity gradients are typically small, except in coastal areas with high run off and rainfall (e.g., Fiordland), although this effect is typically localised (Chiswell et al. 2015). Because observations of precipitation and evaporation over the ocean are sparse and uncertain, trends are difficult to quantify. However, salinity integrates these changes so is a more robust measurement of the hydrological cycle over the ocean.

In the New Zealand region, the surface waters of the Tasman Sea have become more saline, whereas east of New Zealand the surface has freshened. Below the surface, higher salinities were found near the upper ocean salinity maximum (average depth about 100 m) between 1970 and 2005 (Helm et al. 2010). In the Pacific Ocean, the increase in salinity is around 0.09 ± 0.07 and is spatially coherent. Durack & Wijffels (2010) examined the 50-year trend in global ocean salinities by combining historical data from ship based hydrographic casts with Argo data. Around New Zealand they found salinity increasing at the surface in the Tasman Sea, a trend consistent with the results of Hill et al. (2008). East of New Zealand, salinity increases are restricted to the Chatham Rise; this may indicate a combination of higher salinity water transiting from the Tasman Sea via the Subtropical Front and Southland Current, and southward displacement of the Subtropical Front across the Chatham Rise (Durack & Wijffels 2010).

The intermediate layer (average depth about 700 m) has freshened, particularly in the Southern Ocean and in water masses that form in the Southern Ocean and are widespread in the global ocean. This decrease in salinity is particularly measured for Antarctic Intermediate Water and Subantarctic Mode Water (Boyer et al. 2005; Helm et al. 2010), with Böning et al. (2008) reporting freshening in the upper 1000 m of the Southern Ocean of -0.01 per decade between the 1980s and 2000s. This freshening includes the Antarctic Intermediate Water (Bostock et al. 2010) that forms south of New Zealand and influences the waters of the New Zealand region. In contrast to the changes in Southern Ocean waters, little change was found in mid-latitude Southern Hemisphere salinity properties between 1970 and 1992 (Helm et al. 2010), suggesting changes to the north of New Zealand are small and may be delayed due to the longer circulation pathways from the Southern Ocean (Bostock et al. 2010).

Changes in salinity in the deep ocean are harder to detect, due to infrequent sampling; there are no records available for the New Zealand region.

2.3 Stratification and water masses

Key findings:

- In the past 20 years, there has been an increase in near surface stratification of Subtropical waters.
- Even the best models for New Zealand do not agree on the direction of change.
- The depth of the surface mixed layer is projected to decrease by ~15% (14.5 m) across the south west Pacific around New Zealand by 2100.

(i) Observed stratification changes

Water masses are bodies of water with a common formation history and properties. They are used to trace ocean circulation patterns and, because of their common formation history (i.e., the same location and time of year), to determine changes in temperature and salinity. Water masses change little once the water mass has moved below the mixed layer, so changes in a water mass over time largely reflect changes in conditions during formation. Typically, this is the combined effect of long-term trends in surface conditions and forcing, such as, for example, warming of the surface ocean, changes in evaporation and precipitation, and changes in heat fluxes between the ocean and atmosphere.

Changes in water masses also modify the ocean density and hence its stratification (or ‘layering’ of seawater of different temperatures). At the ocean's surface, there tends to be a warm and well-mixed ‘mixed layer’, whereas at depth it is cooler. These layers are separated by the ocean thermocline (the transition layer between shallow and deep water, within which the water temperature changes more rapidly with depth than it does in the layers above and below it). This stratification affects vertical transfer of nutrients and oxygen between shallow and deeper waters.

Changes in ocean temperature and salinity directly change the density of seawater (warm water is less dense than cold; fresh water is less dense than saline). Between 1950 and 2000, seawater density has generally significantly decreased in the upper 200 m of the global ocean due to warming. Seawater density between depths of 200 m and 2000 m has also generally decreased, but not as markedly and not always significantly (Rhein et al. 2013). The decrease in near surface density driven by the corresponding temperature increase is largest in the Pacific Ocean (Rhein et al. 2013). Antarctic Intermediate Water has been changing since the 1960s and is exhibiting a dipole pattern, with salinity and temperature increasing in water deeper than the salinity minimum, whereas lighter waters are cooling and freshening (Böning et al. 2008; Durack & Wijffels 2010; Helm et al. 2010). The salinity minimum in Antarctic Intermediate Water is shoaling (shallowing) by about 40 m per decade, and the water is warming by 0.05–0.15 °C per decade. These changes lead to lighter densities and an associated change in stratification. Antarctic Bottom Water has warmed since the 1980s most noticeably near Antarctica.

Warming will also lead to changes in near-surface structure with an increase in the density discontinuity at the base of the surface mixed layer (Riebesell et al. 2009) and also shallowing (shoaling) of the surface mixed layer, particularly in high-latitude waters where increased freshwater input from precipitation and ice melt will contribute (Jang et al. 2011). With this projected increase in stratification in the near surface ocean water, decreases in vertical nutrient supply, which will reduce nitrate and phosphate availability in the surface ocean, are expected (Behrenfeld et al. 2006). However, a recent review of changes in nutrients levels found no published studies quantifying long-term trends in ocean nutrient concentrations (Rhein et al. 2013).

(ii) Projected stratification changes

Rickard et al. (2016) assessed projected changes in the depth of the seasonal thermocline, defined as the depth where potential density differs from the surface by 0.125 kg m^{-3}, using Earth System Models. The surface mixed layer depth was projected to decrease across the south west Pacific around New Zealand, with a mean decrease by 2100 of 6 m (range 1.5–8 m) under RCP4.5 and 14.5 m (13–18.7 m) under RCP8.5 that is equivalent to a decrease of 15.4% relative to the present-day (Law et al. 2018b). Surprisingly, the two best Earth System Models show contrasting regional responses, with Subantarctic water exhibiting the largest decreases in surface mixed layer depth with one model and the largest increases with the other model (Law et al. 2018b).

Changes to near surface stratification will have effects on primary productivity and hence phytoplankton biomass (Riebesell et al. 2009; Law et al. 2018b; Pinkerton et al. 2019). [See Section 2.6 for further discussion of implications to ocean productivity].

2.4 Wind and waves

Key findings:

- Strengthening and southward movement of the westerly wind band, with peak seasonal average changes of 2–4 knots.
- The pattern of wind change around New Zealand differs depending on the RCP scenario modelled (RCP4.5 vs. RCP8.5).
- Minor increase in average wave height is predicted south and west of the South Island with moderate decreases east of the North Island, with degree of change varying between different RCPs.
- Increase in frequency of extreme wave events to the south and east of New Zealand and decreases on the west coast of the North Island and north of the Bay of Plenty.

(i) Projected changes in wind

The accepted paradigm relating to winds in a warming world is that the strength of the westerly winds will increase, and the mid-latitude westerly wind belt will move south (e.g., Willis et al. 2007). CMIP5 model projections for the area around New Zealand indicate significant changes and also significant differences between seasons (Richard Gorman, NIWA, pers. comm.; Mullan et al. 2011). RCP8.5 changes are stronger than those predicted under the RCP4.5 scenario, with seasonal average anomalies being typically less than 1 m s^{-1} (2 knots) but with peak seasonal average changes of up to 2 m s^{-1} (4 knots). The models indicate strong increases in the vicinity of Cook Strait and south of Stewart Island for most seasons, but these models are of moderately coarse resolution which will impact the accuracy of the predicted wind responses to fine-scale topography (Richard Gorman, NIWA, pers. comm.).

For the RCP4.5 results, the general pattern of change for seasonal averages is of increasing westerlies by about 0.25 to 1 m s^{-1} (0.5 to 2 knots) in the Tasman Sea and south of New Zealand (Richard Gorman, NIWA, pers. comm.). The RCP8.5 projections are quite different, with northeasterly anomalies to the north and east of New Zealand of around 1 m s^{-1} (2 knots), northerly anomalies of around 1 m s^{-1} (2 knots) at around 50° S and westerly anomalies in the Tasman Sea and south west of New Zealand of about 0.5 to 1 m s^{-1} (1 to 2 knots) (Richard Gorman, NIWA, pers. comm.).

(ii) Projected changes in waves

Currently, the highest wave energies occur south of New Zealand generated by the consistently strong winds in the Southern Ocean (Law et al. 2016). The larger swells from the south are progressively moderated by the sheltering effect of the New Zealand landmass, so that the climatologically calmest region around New Zealand is offshore between East Cape and North Cape. Recent analysis indicates that the frequency of extreme wave events is increasing east and south of New Zealand and decreasing off the west coast of the North Island and north of the Bay of Plenty (Ministry for the Environment & Stats NZ 2019).

Under a moderate scenario (RCP4.5 – where emissions are assumed to stabilise mid-century), a minor increase (1 to 3%) in wave height is predicted south and west of the South Island with moderate decrease (-1 to -3%) east of the North Island (Law et al. 2016). Under the highest emissions scenario (RCP8.5) the changes show a similar pattern but with larger amplitudes (Law et al. 2016). Increases in significant wave height range from about 3% south of Stewart Island to about 8% at 60° S. There is a projected decrease in significant wave height of about 10% centered off the Bay of Plenty. Under both scenarios, changes in the Tasman Sea are small, and changes over Chatham Rise show a slight decrease of about -2% to -5%.

Although subtle changes in mean wave climate may not significantly impact marine operations, the frequency of more energetic conditions may. Under a moderate emissions scenario, the percentages of time that significant wave heights exceed 5 m are projected to increase by a few percent south of the

South Island. Conversely, waves greater than 5 m height are projected to be less common east of New Zealand. For a stronger emission scenario, the frequency of waves with a significant height (over 5 m) increases slightly in the Tasman Sea and has a broad increase of a few percent south of about 46° S, with a peak change south of Stewart Island of about 5% (Law et al. 2016).

2.5 Ocean currents and circulation

Key findings:

- Observed increase in sea surface height in the South Pacific Ocean around New Zealand.
- Intensification of South Pacific subtropical gyre over last two decades.
- Southward expansion of the East Australian Current.
- Poleward shift of the Antarctic Circumpolar Current.

(i) Observed changes in circulation

There has been a broad increase in sea surface height between 35° S and 50° S in the South Pacific Ocean, driven by intensification and poleward migration of the westerly winds that generate positive and negative wind stress curl anomalies north and south of 50° S. This increase in sea surface height has caused the southern limb of the South Pacific subtropical gyre to intensify over the last two decades (Cai 2006; Qiu and Chen 2006; Roemmich et al. 2007). The intensification has extended deeper than 1800 m in the South Pacific Ocean (Roemmich & Gilson 2009). There has also been an associated southward expansion of the East Australian Current (Hill et al. 2008), which is expected to promote the establishment of subtropical species east of Tasmania that currently only occur as vagrants in warm La Niña years (Ridgway & Hill 2009).

Further south, observations of temperature, salinity, and sea surface height indicate that the ACC has shifted poleward by an average of about 60 km (Böning et al. 2008; Morrow et al. 2008; Sokolov & Rintoul 2009). However, the position of the Antarctic Circumpolar Current is strongly linked to the seafloor topography in the New Zealand region, in particular with the Macquarie Ridge and Campbell Plateau, which steer this current south of its mean latitude (Chiswell et al. 2015). The strong link between the position of the Antarctic Circumpolar Current and bathymetry suggests that there may only be a weak effect of climate change on its position south of New Zealand.

2.6 Oxygen

Key findings:

- Decreased oxygen concentrations in ocean thermocline since 1960, partially explained by ocean warming.
- Modelling of dissolved oxygen for the New Zealand region suggests little significant change is projected for the end of century under RCP8.5.

Dissolved oxygen concentrations within the ocean thermocline (the transition layer between warmer well-mixed water at the ocean's surface and cooler deep water below) have generally decreased since 1960 (Keeling et al. 2011; Keeling & Manning 2014). Between 50° S and 50° N dissolved oxygen concentrations decreased at about 400 m depth by 0.63 μmol kg^{-1} per decade between 1960 and 2010 (Stramma et al. 2012). This long-term reduction in oxygen in the open ocean is consistent with warming of the ocean, because warmer waters have lower solubility for dissolved oxygen. Additionally, increased stratification [see Section 2.3] is expected to decrease the transport of oxygen from the surface ocean into the deep ocean, and enhanced respiration at warmer temperatures will increase the uptake of dissolved oxygen. Helm et al. (2011) suggest that 15% of the reported oxygen decline between 1970 and 1990 could be explained by warming, with the remainder explained by reduced ventilation due to increased stratification.

(i) Observed changes in dissolved oxygen

There are no data available with which to detect trends or changes in dissolved oxygen concentrations in New Zealand waters, specifically.

(ii) Projected changes in dissolved oxygen

Modelling of dissolved oxygen for the New Zealand region suggests little significant change is projected between present day and end of century under RCP8.5, except for in deeper waters (over 2000 m) (Figure 4; Sara Mikaloff-Fletcher, NIWA, unpublished data).

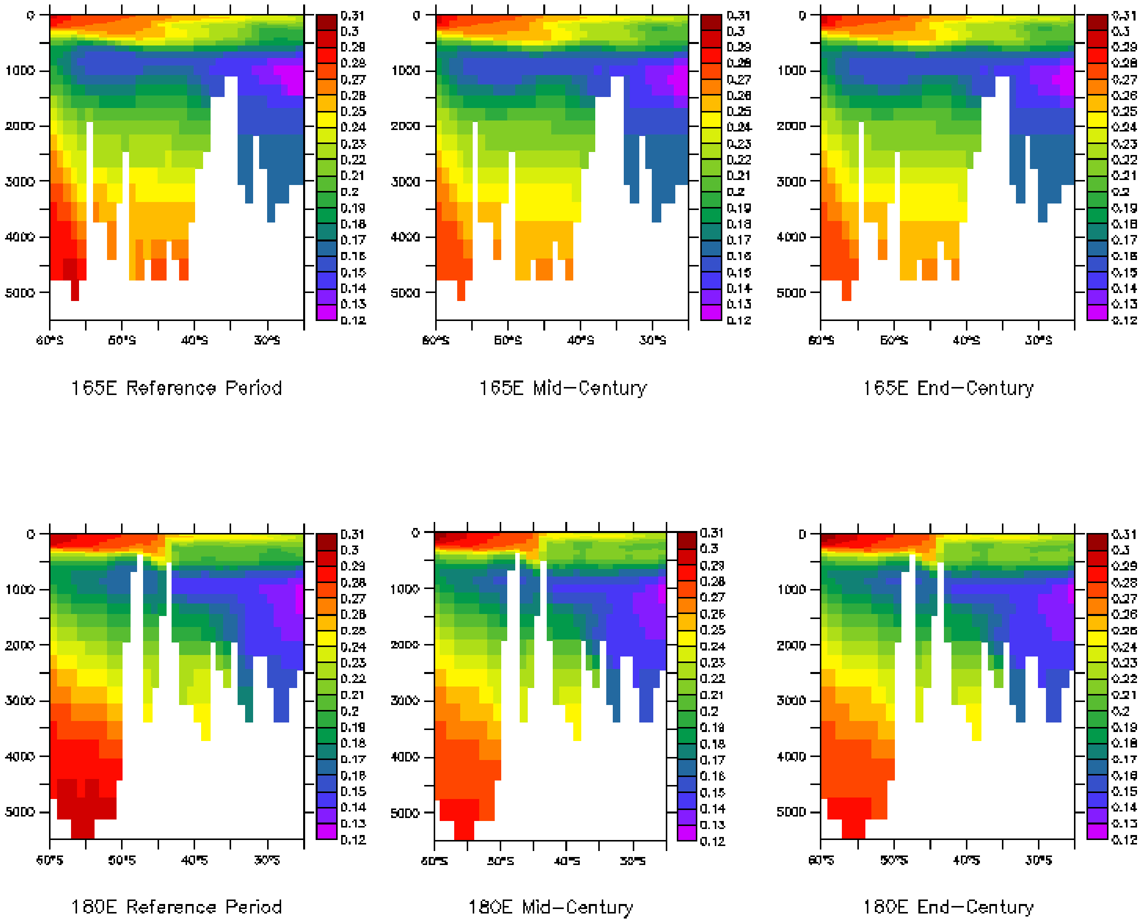


Figure 4: Dissolved oxygen vertical profiles along 165° S (upper three plots) and 180° S (lower three plots) modelled for present-day (left), and projected for mid-century (middle) and end-century 2100 (right). Modelled using the GFDL-Earth System Model 2 global coupled climate-carbon earth system model (Dunne et al. 2012) under the RCP8.5 scenario. The y-axis is ocean depth (m), and the colour scale indicates dissolved oxygen concentration (mol m^{-3}). (Figure courtesy of Sara Mikaloff-Fletcher, NIWA.)

2.7 Ocean productivity

Key findings:

- Observed changes in chlorophyll *a* (a commonly used indicator of primary productivity in the ocean) between 1997 and 2018 were generally negative in subtropical waters and generally positive in Subantarctic waters.
- The highest observed trends in chlorophyll *a* 1997–2018 were positive (+2% per year) and found in the Subtropical Front (west of Fiordland and over the Chatham Rise).
- Most coastal (within 20 km of the shore) changes in chlorophyll *a* between 2002–2018 followed offshore changes, but there were some areas where the inshore and offshore trends differed, likely indicative of land-use change or local oceanographic effects.
- The magnitude of changes in primary production projected for around New Zealand by 2100 (using the two best Earth System Models for New Zealand) are lower than the global average, inferring that regional productivity may be relatively less affected than other parts of the global ocean.
- Changes in primary productivity in the New Zealand region are related to water mass with decreasing trends generally observed in Subtropical waters and increasing trends observed over the last two decades in Subantarctic waters.

Observations of surface chlorophyll *a* are available from the SeaWiFS and MODIS sensors (NASA) from September 1997 to 2018 (Pinkerton et al. 2019). Continuous Plankton Recorder (CPR) surveys collect spatial-temporal patterns of zooplankton, with the observation that changes to zooplankton can indicate regime shifts (e.g., Möllmann et al. 2008) and can potentially be used as early warning indicators of marine ecosystem health (Pace et al. 2013). New Zealand Biodiversity Research Advisory Group (BRAG) projects contribute to the Scientific Committee for Antarctic Research (SCAR) Southern Ocean CPR data collection established in 1991 by the Australian Antarctic Division to map the Southern Ocean, quantifying distributions of epipelagic plankton, including phytoplankton, zooplankton, and euphausiid (krill) life stages, in New Zealand's EEZ and transit to the Ross Sea, Antarctica (Pinkerton et al. 2010, 2020).

(i) Observed changes in ocean productivity

SeaWIFS and MODIS sensors indicate positive trends in chlorophyll *a* (indicative of increasing productivity) in the Subtropical Front (west of Fiordland and over the Chatham Rise). Negative trends in chlorophyll *a* (indicative of decreasing productivity) were found around Northland and the northeast continental slope. Long-term changes in chlorophyll *a* observed by satellite were generally negative in subtropical waters and generally positive in Subantarctic waters. In some subtropical waters around New Zealand, monthly chlorophyll *a* anomalies correlate reasonably strongly (R up to ~0.6) with the IPO (Interdecadal Pacific Oscillation) (Pinkerton, NIWA, unpublished analysis).

Continuous Plankton Recorder surveys suggest that changes to environmental conditions over the last 20 years (1997–2018) are likely to have led to increases in the abundance of most broad taxonomic groups of zooplankton in the Southern Ocean, with copepods, Foraminifera, and *Fritillaria* spp. especially likely to have benefitted. In contrast, the environmental conditions for pteropods (small marine snails living in the water column) seem to have worsened over the last 20 years, particularly over the Ross Sea shelf (Robinson et al. 2019).

(ii) Projected changes in ocean productivity

Projections of surface chlorophyll *a* by the two best Earth System Models for New Zealand waters indicate a minor decrease under RCP4.5 of about 0.01 mg m^{-3} by 2100 (-5% of present-day mean concentration), and a decrease of about 0.015 mg^{-3} (-7.5% present-day) by 2100 under RCP8.5 (Law et al. 2018b). The regional range in the projected change (+0.06 to -0.06 mg m^{-3}) is low and uniform, although one Earth System Model projects greater decreases (up to 0.5 mg m^{-3}) in Subtropical Front waters south of Australia and New Zealand. This is reflected in projections of net primary production (NPP) using the two best Earth System Models (Rickard et al. 2016). There is no significant change in

NPP by 2050, with decreases of 0.4 and 1.5 mmol C m^{-2} d^{-1} (-1.2% and -4.5% of present-day values, respectively) by 2150 under RCP4.5 and 8.5, respectively, with the largest NPP decline projected for subtropical waters north of 40° S, which already experience low NPP. These estimates are considerably lower than the respective global averages, of -3.6% and -8.6% (Bopp et al. 2013), implying that productivity around New Zealand may be relatively less affected by climate change. However, the Earth System Model projections from the inner ensemble of Rickard et al. (2016) show a broad range of change in NPP by 2100 under RCP8.5, from 0.3 to 3.7 mmol C m^{-2} d^{-1} (-0.9 to -11% present day).

Overall, surface waters north of the Subtropical Front are expected to warm and increase in dissolved iron concentration but decrease in other macronutrients and chlorophyll *a* and NPP over the next 100 years. South of the Subtropical Front surface waters will experience less warming, with a decline in iron, phosphate, and nitrate concentration, but no significant change in phosphate, silicate, and chlorophyll *a* concentration and an increase in NPP (Law et al. 2018b). However, the magnitude of these changes will remain dependent on future changes in climate, with models providing only a guide to future changes.

Direct observation of recent trends in primary productivity in the New Zealand region using satellite ocean-colour sensors have largely focused on the surface waters, and knowledge of the effects of climate change on subsurface algal productivity (deep chlorophyll maxima) is limited. Given the evidence of warming and freshening from large scale observations and studies, changes are anticipated in intermediate and deep waters as well. Clarifying the direction and magnitude of these sub-surface changes will be important for understanding future change in total ocean productivity in the New Zealand region. Further analysis of the most useful CMIP5 Earth System Models identified by Rickard et al. (2016) as an optimal ensemble for future predictions of ocean climate around New Zealand could provide predictions for sub-surface productivity.

2.8 Detrital flux (non-living biological material important for benthic and mesopelagic consumers)

Key findings:

- Observed particle fluxes show typical rates relative to the global average in subtropical waters and lower than average rates in Subantarctic waters.
- Models project decreases in detrital flux in most of the South West Pacific subregions by 2100, with largest projected declines of 11.1% and 23.6% under RCP4.5 and 8.5, respectively.

The upper water column contains non-living particulate matter ('detritus') which includes material such as dead phytoplankton and zooplankton cells, phytoplankton exudates, and zooplankton faecal pellets. Near the coast especially, this material can also include abraded algal and sessile material (e.g., macroalgae), and inorganic particulate material from riverine run-off, re-suspension of benthic sediments, and wind-borne dust. A proportion of the upper-ocean detritus exits the surface mixed layer and sinks down through the water column – this sedimenting material is called the *detrital flux*. Sinking rates can be fast for faecal pellets (up to about 100 m d^{-1}) but slow (about 10 m d^{-1}) for aggregations of finer particulate material ('marine snow') (Parsons et al. 1984). As it sinks, this material loses organic compounds by leaching, bacterial degradation, and direct consumption. A portion of the sedimenting material eventually reaches the sea-bed, the amount depending on factors including water depth and temperature, and the type of sedimenting material (Lutz et al. 2007).

(i) Observed detrital flux

Measured particle flux rates are low in Subantarctic water (about 1.9 mg C m^{-2} d^{-1}), because of low primary production rates there. Particle flux rates in subtropical waters are typical of the global average (about 3 mg C m^{-2} d^{-1}), although the lithogenic contribution is greater (Nodder et al. 2016).

(ii) Projected changes in detrital flux

Following the projected changes in primary productivity rates in the New Zealand region, detrital flux is projected by Earth System Models to decrease in the New Zealand region under RCP4.5 and 8.5, respectively, by 1.3% and 4.5% by 2050, and 4.5% and 12% by 2100. The RCP8.5 projections are outside the range of present-day interannual variability (Law et al. 2018b). Projected decreases in global export production under RCP8.5 for 2100 are 7–18% (Bopp et al. 2013), and, consequently, reductions in New Zealand waters are consistent with global projections. Analysis of the spatial variation in detrital flux confirms a decrease in most of the South West Pacific subregions, with subtropical waters in region 2 (see Figure 3) experiencing the largest proportional decline, of 11.1% and 23.6% under RCP4.5 and 8.5, respectively, by 2100. However, the Chatham Rise (region 6 in Figure 3) shows a decline of 12.6% by End-Century. Because this region supports the most productive fishery region in New Zealand waters, there are implications of this change for fish food supply.

These predictions should be taken alongside the observed increase in chlorophyll *a* in the Subtropical Front between 1997 and 2018 in the ocean colour satellite data. It is likely that this increased chlorophyll *a* will have led to an increase in detrital flux in the Subtropical Front which includes the Chatham Rise region. To anticipate the future effects of climate change in the Subtropical Front region will require a better understanding of why chlorophyll *a* has increased in this region over the last 20 years and a better ability to model the frontal regions at higher spatial resolution than is currently possible in CMIP5 global biogeochemical models.

2.9 Ocean acidification

Key findings:

- Seawater pH offshore from New Zealand's Otago coast has declined from 8.09 to 8.065 between in 1998 and 2013, representing a statistically significant decrease of 0.0013 per year. This is an increase in acidity of 7.1% and is consistent with that recorded by time series observations in other oceanic regions of the world.
- There are no long-term records with which to evaluate change in near coastal pH around New Zealand.
- Maps have been generated of the depth of the Aragonite Saturation Horizon (the depth below which dissolution of solid aragonite, a form of calcium carbonate, occurs) in New Zealand waters. This modelling shows a shoaling (shallowing) of the Aragonite Saturation Horizon at the South Polar Front.
- Oceanic pH for New Zealand is projected to decline to pH about 7.75 by 2100 (using the RCP8.5 scenario).

Rising atmospheric CO_2 is causing 'ocean acidification', a collective term used to describe the changes in different components of the ocean carbonate system (Orr et al. 2005), as a result of the reaction between CO_2 and water forming a weak acid. This change is most apparent as a decrease in pH and carbonate ion concentrations and increases in concentrations of dissolved carbon dioxide (pCO_2) and bicarbonate ions. These changes in water chemistry have the potential to impact a variety of marine flora, fauna, and ecosystems (Fabry et al. 2008). In coastal waters, the variability and rate of change in pH differ from those in the open ocean, due to the influence of additional (non-atmospheric) sources of CO_2. These include terrestrial run-off, which contributes organic matter and nutrients that stimulate respiratory production of CO_2 in shallow coastal regions, and low alkalinity freshwater.

(i) Observed ocean acidification

The variability in pH and the carbonate system in Subantarctic waters has been monitored off the Otago coast at bimonthly intervals since 1998 (the 'Munida Time Series'; Currie et al. 2011; Law et al. 2018a). This monitoring is the longest pH time series record in the Southern Hemisphere to date and, with pH declining from 8.09 in 1998 to 8.065 in 2013, indicating a statistically significant decrease of 0.0013 per year (Bates et al. 2014). Ocean pH has increased by 7.1% in the past 20 years.

This change is consistent with that recorded by time series observations in other oceanic regions (Bates et al. 2014) and also with the increasing trend in atmospheric CO_2 at Baring Head Station near Wellington (see figure 1 of Vance et al. 2020).

There are no long-term records with which to evaluate change in seawater pH around coastal New Zealand. Nevertheless, measurements of pH in the Firth of Thames show this area already experiences seasonal pH levels that are significantly lower than expected from equilibration with atmospheric CO_2 in autumn (Law et al. 2018a). The New Zealand Ocean Acidification-Observing Network (NZOA-ON), initiated in 2015, is now monitoring the rate and magnitude of coastal acidification at 14 sites around New Zealand. Although the NZOA-ON cannot yet be used to infer change, it is providing information on the range of variability in pH at sites over time, and between sites around New Zealand (Vance et al. 2019; https://marinedata.niwa.co.nz/nzoa-on/). The New Zealand network is linked into the Global Ocean Acidification Observing Network (GOA-ON; http://www.goa-on.org/).

The paucity of observational data for the carbonate system has been addressed by developing multiple linear regression (MLR) algorithms to estimate alkalinity and dissolved inorganic carbon (DIC) in intermediate and deep waters (south of 25° S) from temperature, salinity, and dissolved oxygen (Bostock et al. 2013). These algorithms have in turn been used to calculate carbonate saturation states and depths. The depth at which seawater is saturated with aragonite is termed the Aragonite Saturation Horizon (ASH). Below this depth, the ocean is under-saturated with respect to aragonite, meaning dissolution of solid aragonite will occur (with implications for animals that have shells/skeletons that comprise this carbonate polymorph). The maps of the Aragonite Saturation Horizon that result from this modelling show a shoaling (shallowing) of this horizon at the South Polar Front (Bostock et al. 2013).

(ii) Projected ocean acidification

Ocean pH in New Zealand waters has been projected for each of the four Representative Concentration Pathways. The RCP4.5 scenario projects a stabilisation in pH at about 7.95 in New Zealand waters in the latter half of this century, approximately 0.13 lower than the present-day oceanic pH of 8.08. The RCP8.5 projection indicates a decline to pH 7.75 by 2100. The projected mean decrease of 0.335 for the New Zealand region is consistent with projections under RCP8.5 for Australian waters (0.304–0.322; Lenton et al. 2015), and the global ocean (0.30–0.35; Bopp et al. 2013; Sweetman et al. 2017) by the end of the century.

Seasonality in pH results in a relatively large annual range of about 0.05, which obscures differences in the different RCP projections until about 2035 (Law et al. 2018a). However, pH subsequently deviates under the different RCPs, declining to 7.985 by 2050 and 7.95 by 2100 under RCP4.5, equivalent to respective increases of 32% and 42% in hydrogen ion concentration relative to the present-day (Law et al. 2018a). The RCP8.5 projection shows a steeper pH decline to 7.94 and 7.77 by 2050 and 2100, respectively, with a decline of 0.33 pH units by 2100 (Law et al. 2018a).

Minor regional variation in the projected change in pH is evident, with higher projected pH in northern subtropical waters and the East Australian Current and lower pH in the south by 2100 (Law et al. 2018b). This meridional gradient of about 0.03 partially reflects the higher solubility of CO_2, and thus lower pH, in colder water. The marginally higher pH in the Subtropical Front over the Chatham Rise may reflect warming or, alternatively, elevated CO_2 uptake by phytoplankton in frontal waters. Conversely, the lowest projected pH by 2100, of 7.7, occurs in polar waters south of 55° S.

2.10 Coastal erosion and sediments

Key findings:

- More frequent input of freshwater and sediments to coastal regions are anticipated, due to changes in frequency and intensity of rainfall and storm events.
- Due to differences in their geography, geology, and coastal environmental conditions, the east coasts of both North and South islands have higher sensitivities to climate driven coastal erosion than their west coasts.

Rates of coastal erosion, and the amount of sediment that is delivered to coasts and estuaries, are influenced by multiple drivers that are either directly or indirectly influenced by climate change. Catchment geography and geology influence the likelihood of sediment erosion, and land-use in the surrounding catchment has a major influence on the magnitude of sediment loading to adjacent coasts and estuaries (Murray 2013; Suyadi et al. 2019). Marine-based sediment inputs, and wave and tidal exposure, also influence sediment erosion and transport through wave-driven alongshore transport (Ministry for the Environment 2008; Komar & Harris 2014).

Most fine terrestrial sediment eroded from New Zealand catchments is transported from the land via a river to an estuary or coastal zone during storm events. The frequency and duration of storm events and associated runoff largely determines the sediment load input to the estuary. Other key drivers include sea level rise, waves and tides associated with storm events, and the supply of sediment from both land-based and marine sources (Church et al. 2008; McGlone et al. 2010; Kettles & Bell 2015). Sea level around New Zealand has risen, on average, 2.44 (±0.10) mm per year between 1961 and 2018. This is a faster rate than between the start of New Zealand records (around 1900) and 1960 (1.22 ±0.12 mm per year (Ministry for the Environment & Stats NZ 2019). A further rise of 0.3–1.0 m is projected to occur by 2100, depending on global greenhouse gas emissions (Climate Change Adaptation Technical Working Group 2017). Sea level rise will continue to modify coast lines and their erosion processes in the future.

Soil erosion from land-based sources is linked with habitat degradation in estuaries and coasts in many regions of New Zealand (e.g., Morrison et al. 2009). Once land-derived sediments reach estuaries or coasts, the tide, wind, and wave interaction with existing morphology will largely determine where the sediment will move to, deposit, or later erode from. Increasing sedimentation deposition can result in increasingly muddier soft sediment substrates and smothering of benthic habitats, particularly affecting sessile epifaunal and infaunal species and communities, and hard substrates such as rocky reefs that provide habitat structure for fish and invertebrates (Thrush et al. 2004). Sediment erosion and deposition is also associated with changes in seabed height that affect habitat suitability for intertidal and subtidal species (e.g., Suyadi et al. 2019). Finally, sediment erosion to coastal areas may also increase water column turbidity, affecting productivity of phytoplankton (Figure 5), seafloor microphytobenthos, and macroalgae through modification of light levels. Benthic communities are affected by elevated suspended sediments indirectly through effects on their primary food sources and directly through interference with their filter feeding activities resulting in reductions in benthic species that provide habitat structure for fish and invertebrates (Thrush et al. 2004).

(i) Observed changes in sedimentation

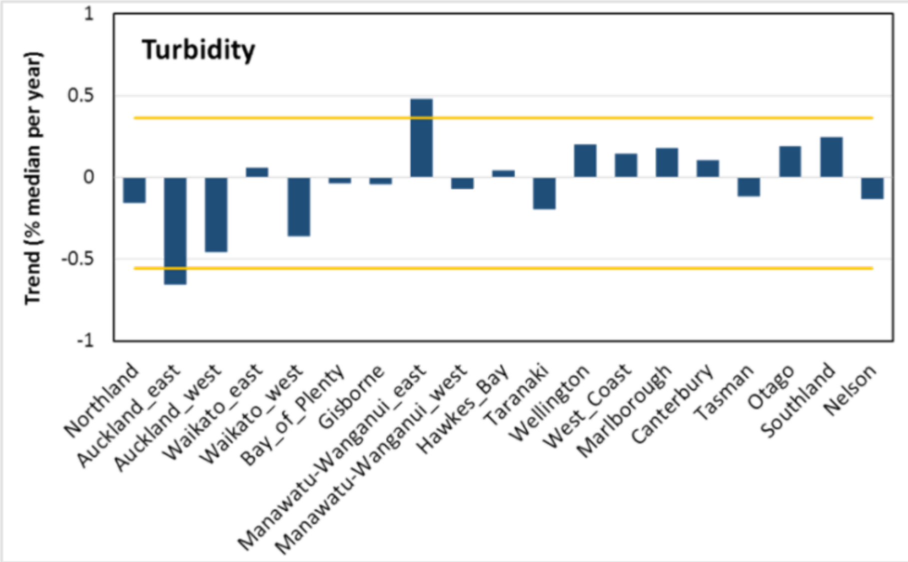
In situ quantification of sedimentation and associated processes has been performed in a number of locations, particularly the upper North Island, Wellington Harbour, Porirua Estuary, and Banks Peninsula (Rouse et al. 2017). Rates of sediment deposition range from 1–2 mm y^{-1} in large exposed harbours (e.g., Tauranga Harbour, Manukau Harbour), 2–5 mm y^{-1} in typical intertidal regions in estuaries, to 10 mm y^{-1} in sheltered tidal creeks. Highest rates, of 25 mm y^{-1}, have been measured since the 1920s in the southern Firth of Thames, primarily due to changing land use (Swales et al. 2015).

Rainfall events and coastal erosion contribute to changes in water quality. Trends in water quality between 2002 and 2017 were derived by applying coastal processing algorithms to ocean colour satellite data from NASA's MODIS-Aqua sensor (Figure 5; Pinkerton et al. 2017). Trends over this 15-year period were obtained by de-seasonalised Mann Kendall analysis, with estimation of the magnitudes of trends by non-parametric Sen slope (Sen 1968). At the level of Regional Council jurisdictions, there were only two significant trends in turbidity (indicative of long-term changes to suspended sediment concentrations) and 12 significant trends in chlorophyll *a* (both positive and negative) which are indicative of widespread changes to coastal phytoplankton productivity round New Zealand (Figure 5b and c, respectively).

a

Figure 5: Coastal trends in water quality between 2002 and 2017 from MODIS-Aqua data. a: Regional Council areas. (Figure adapted from Pinkerton et al. 2017; continued on next page.)

b



c

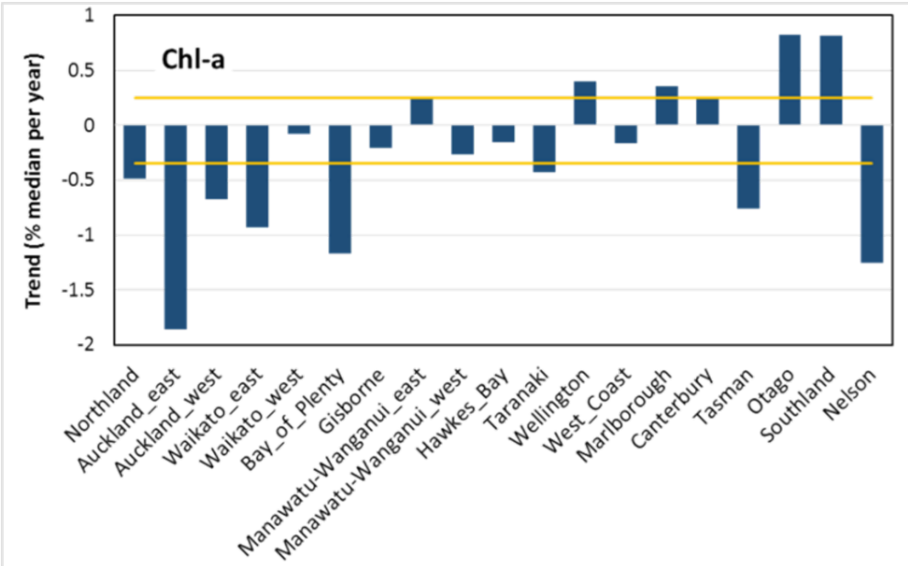


Figure 5: ***continued.*** **Coastal trends in water quality between 2002 and 2017 from MODIS-Aqua data. b: Trends in turbidity (indicative of suspended sediment concentration); c: Trends in chlorophyll *a* concentration (indicative of coastal productivity). Orange lines indicate the 95% confidence intervals, so that bars extending outside this range are considered significant. (Figure adapted from Pinkerton et al. 2017.)**

(ii) Projected changes in sedimentation

Rainfall is predicted to change significantly in the coming decades, with increased precipitation in the west, and reduced precipitation in the east, interacting with catchment topography and sensitivity to erosion (Lundquist et al. 2011; Mullan et al. 2011; Reisinger et al. 2014). Intense rainfall events are predicted to increase in intensity in most regions of New Zealand due to changing climatic patterns, resulting in increased soil erosion and transport and deposition of sediments in estuaries and coastal waters (Thrush et al. 2004). It is expected that more frequent input of freshwater and sediments to coastal regions will occur due to changes in frequency and intensity of rainfall and storm events (Mullan et al. 2011; Reisinger et al. 2014).

The current and future sensitivity of New Zealand's shorelines to climate change-induced erosion has been evaluated at a national scale, classifying the susceptibility of sedimentary segments to coastal erosion (see Figure 6; Goodhue et al. 2012). This classification was underpinned by NIWA's coastal classification and weighted based on geomorphic and coastal variables (Goodhue et al. 2012). The classification demonstrates higher sensitivities on the east coasts of the North Island and South Island to sediment erosion. Key drivers of coastal erosion are wave exposure, tidal range, sediment budget, and proximity to tidal inlets. West coast shores of both islands show lower sensitivities to climate driven coastal erosion, primarily due to higher typical levels of wave energy.

Climate driven sedimentation interacts in complex ways with 'coastal squeeze', where sea level rise shifts intertidal habitats shoreward, but natural or human modifications prevent shoreward expansion of coastal or estuarine habitats (Bell et al. 2001; McGlone et al. 2010; Kettles & Bell 2015). Mean sea levels have risen at an average rate of 1.7 ± 0.1 mm y^{-1} since 1900 (Lundquist et al. 2011; Hannah & Bell 2012), which is within the range of the global average. Plausible increases are likely to be 0.3–1.0 m by 2100 (Climate Change Adaptation Technical Working Group 2017), but higher rises cannot be ruled out (Lundquist et al. 2011; IPCC 2014). When combined, these processes are expected to increasingly expose shorelines to more frequent storm damage and reduce space and capacity for intertidal ecosystems. For example, with 0.8 m of sea level rise, the current one in one-hundred-year high tide will be exceeded at over 90% of high tides (Royal Society of New Zealand 2016).

Figure 6: Sensitivity to climate-change induced coastal erosion for 'soft' segments of the New Zealand coast. (Figure from Goodhue et al. 2012, with permission.)

2.11 Use of projections to identify regional vulnerabilities

Most of the parameters above were used to generate future projections of the open ocean subregions (identified in Figure 3) more vulnerable to climate change around New Zealand. Sub-regions were identified where the maximum projected change occurred for two or more variables (Law et al. 2018b). The Chatham Rise will experience a significant change in a number of parameters by 2100, although the spatial extent of this region of vulnerability varies, extending southward with the Subtropical Front east and south of the South Island with one Earth System Model, and into Subantarctic Water with the other (Law et al. 2018b). The two best Earth System Models show a decrease in primary production and particle export along the northern extent of the Chatham Rise and identify polar waters south of New Zealand and subtropical waters north of 30° S as potentially vulnerable regions (Figure 7).

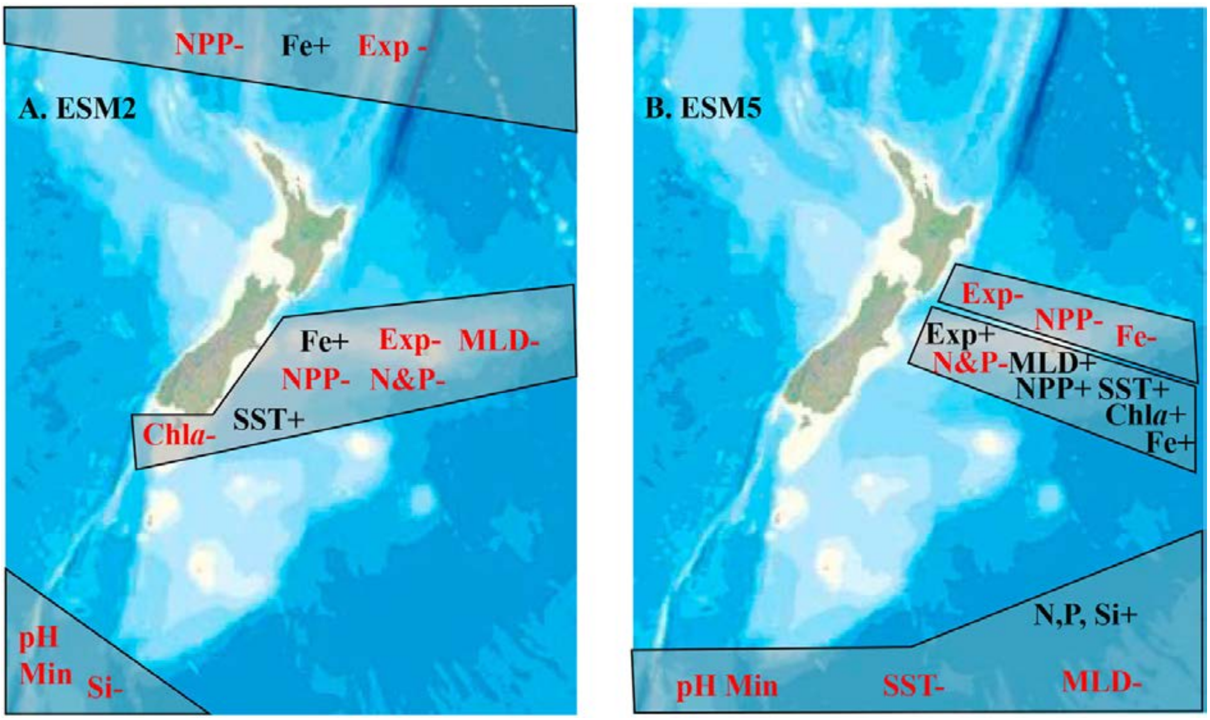


Figure 7: Regional extremes for climate-sensitive variables in the surface ocean around New Zealand projected for 2080–2100 using A, Earth System Model 2 and B, Earth System Model 5. The shaded areas represent potentially vulnerable regions, where two or more variables show significant change relative to the New Zealand mean. The change response is indicated by colour and sign, with a significant decrease indicated in red with a - symbol, and a significant increase in black with a + symbol. Key: SST: Sea Surface Temperature; MLD: Mixed Layer Depth; N&P: Nitrate and Phosphate; Si: Silicate; Fe: Dissolved Iron; Chla: Chlorophyll *a*; NPP: Integrated Primary Production; Exp: Particle flux; pH Min: lowest regional pH. (Figure reproduced from Law et al. 2018b, with permission.)

3. EVALUATION OF FISHERIES AND ENVIRONMENTAL CHANGE — GENERAL INFORMATION

This section summarises New Zealand-specific information on how changes in some of the climate variables discussed in Section 2 might affect fisheries.

Investigations on the impacts of changing climate variables on New Zealand fisheries and aquaculture include wide-ranging studies, covering many species and regions around New Zealand (e.g., Dunn et al. 2009; Bradford-Grieve & Livingston 2011; Hurst et al. 2012; MacDiarmid et al. 2012; Capson & Guinotte 2014), and species-specific investigations (including of hoki, snapper, gemfish, red cod, tuna, southern blue whiting, rock lobster, school shark, orange roughy, and jack mackerel; see Pinkerton 2017). Dunn et al. (2009) investigated variations in abundance and commercial catch rates of 56 New Zealand fish species in relation to 20 climate indices over periods of 5–30 years; no consistent changes in abundance or catchability of 'warmer-water' or 'colder-water' species were found over this period. These authors did however find evidence of statistically significant relationships between climate variables [e.g., sea surface temperature and height, Southern Oscillation Index, and the 'Zonal', 'Trough', and 'Blocking' regimes of Kidson (2000)] and the productivity (i.e., biomass indices or year class strengths) of six species of New Zealand fish (Dunn et al. 2009). Hurst et al. (2012) reported some general observations on recent trends in some of the key ocean climate indices that have been found to be correlated with a variety of biological processes among fish (including recruitment fluctuations, growth, distribution, productivity, and catch rates). With reference to the influence of environmental predictors on fish populations, it should, however, be noted that Francis (2006) cautioned that "*when many environmental variables are considered, it is easy to draw conclusions that exaggerate the ability to predict recruitment … our ability to measure the reliability of recruitment predictors is typically poor*". In addition, recruitment trends are often not measured reliably, or consistently, because of data and/or methodological changes (e.g., Francis et al. 2006), and the causal mechanisms for estimated recruitment trends are generally unknown, and usually not investigated (Fisheries New Zealand 2020a).

3.1 Detrital flux

For 38 species of fish caught in New Zealand waters, Pinkerton et al. (2016) related estimates of detrital flux in the water column and at the seabed to the distribution of mesopelagic and benthic/demersal fish. This measure of '*fish flux*' provided an estimate of future changes in flux specific to particular species of fish. Future changes in *fish flux* based on CMIP5 models were obtained under the RCP4.5 and 8.5 scenarios for 50 and 100 years hence (Law et al. 2016). Pinkerton et al. (2016) found that all projected changes in *fish flux* were negative (decreases), ranging from -2.2 to -24.6%, with greater changes at end of the century than mid-century, and under RCP8.5 relative to RCP4.5. The species predicted to be most affected by future climate change via reductions in particulate flux were northern spiny dogfish, gemfish, frostfish, and tarakihi, whereas species least affected were black oreo, barracouta, southern blue whiting, and blue warehou (Table 1).

Table 1: Changes to flux for key New Zealand fish species. Species are sorted in decreasing order of change of *fishFlux* averaged across both RCP scenarios and both time periods. * indicates that the change is greater than twice the present-day variability ('range'). [From Pinkerton et al. 2016.]

		Present-day *fishFlux* ($mgC\ m^{-2}\ d^{-1}$)		Change (%)			
					RCP 4.5		RCP 8.5
Code	Name	Mean	Range (2 SD)	2036–2055	2081–2100	2036–2055	2081–2100
NSD	Northern spiny dogfish	15.1	8.4	-10.3 *	-14.7 *	-14.9 *	-24.6 *
SKI	Gemfish	17.4	6.8	-8.9 *	-13.5 *	-14.6 *	-22.9 *
FRO	Frostfish	18.9	6.3	-8.4 *	-12.1 *	-13.7 *	-22.9 *
TAR	Tarakihi	18.7	6.0	-8.6 *	-11.7 *	-13.2 *	-21.8 *
WHX	White rattail	6.6	15.4	-8.3	-11.5	-11.9	-14.5
SCH	School shark	16.9	5.2	-7.6 *	-9.3 *	-10.8 *	-17.6 *
JMD	Horse mackerel	18.5	5.4	-7.3 *	-10.1 *	-10.6 *	-17.2 *
EPT	Black cardinal fish	6.2	11.2	-6.9	-8.6	-8.9	-15.0 *
SND	Shovelnose dogfish	8.2	16.4	-7.9	-8.4	-9.3	-13.6
COL	Oliver's rattail	8.6	11.9	-7.4	-7.9	-8.2	-14.9 *
SSO	Smooth oreo	4.7	26.5	-6.8	-8.0	-8.7	-14.3
CBO	Bollons' rattail	13.4	9.3	-7.2	-7.7	-8.6	-13.9 *
WWA	White warehou	12.8	9.2	-7.2	-6.7	-8.1	-14.4 *
SWA	Silver warehou	14.1	7.1	-7.0	-6.7	-7.9 *	-14.3 *
ORH	Orange roughy	5.6	17.7	-6.3	-7.8	-8.8	-13.0
RBM	Ray's bream	13.4	6.9	-6.9	-6.9	-8.1 *	-14.0 *
RIB	Ribaldo	6.1	14.9	-6.3	-7.7	-7.9	-13.8
LDO	Lookdown dory	12.9	12.5	-8.2	-6.3	-8.2	-12.8 *
BSH	Seal shark	10.9	6.8	-5.5	-8.3 *	-7.6 *	-14.0 *
HAK	Hake	7.7	13.0	-6.6	-7.3	-7.7	-13.8 *
HOK	Hoki	10.2	10.4	-6.8	-6.7	-7.6	-14.2 *
SPE	Sea perch	14.4	9.5	-7.1	-6.4	-8.3	-12.8 *
HAP	Hāpuku	16.1	5.2	-6.0 *	-6.7 *	-6.8 *	-14.5 *
RBT	Redbait	15.3	5.3	-6.3 *	-6.7 *	-7.1 *	-13.6 *
RCO	Red cod	15.6	5.4	-5.8 *	-7.2 *	-7.1 *	-13.0 *
SPD	Spiny dogfish	13.4	7.2	-5.9	-6.5	-7.1	-13.5 *
JMM	Murphy's mackerel	15.4	5.3	-6.0 *	-6.9 *	-6.9 *	-13.1 *
SOR	Spiky oreo	9.2	21.6	-7.4	-6.5	-7.4	-11.1
BNS	Bluenose	20.0	5.1	-4.1	-7.1 *	-5.8 *	-14.0 *
JAV	Javelin fish	7.4	16.1	-5.6	-6.2	-7.3	-11.8
GSP	Pale ghost shark	7.1	17.9	-5.5	-6.5	-7.2	-11.2
LIN	Ling	8.1	14.9	-4.8	-6.3	-7.2	-12.0
LSO	Lemon sole	14.7	14.7	-6.7	-5.4	-6.0	-11.8
BYX	Alfonsino	14.4	9.0	-5.7	-5.3	-6.1	-10.8 *
WAR	Blue warehou	16.0	6.2	-4.7	-6.0	-5.6	-11.3 *
SBW	Southern blue whiting	6.0	34.4	-4.2	-4.6	-6.4	-8.5
BAR	Barracouta	22.6	8.6	-3.2	-4.9	-4.3	-8.3
BOE	Black oreo	12.3	11.5	-2.2	-2.9	-3.3	-5.7

3.2 Sedimentation and sediment resuspension

Climatic changes in the frequency and severity of storm events, and the associated elevated sedimentation rates and resuspension of seafloor sediments, are a recognised threat to coastal zones, many of which are important habitat for fish (Thrush et al. 2004). Thus, increased sedimentation and resuspension is likely to result in a number of direct and indirect impacts on coastal and estuarine fisheries. Increased turbidity and decreased light penetration can negatively impact primary productivity, influencing habitat forming species such as kelp (e.g., *Macrocystis pyrifera*, managed under the QMS system since 2011) and filter feeding species such as key shellfish fisheries (mussels, *Perna canaliculus*; cockles, *Austrovenus stutchburyi*; pipi, *Paphies australis*; Hawkins et al. 1999; Cummings & Thrush 2004). Suspended sediment loads, in combination with rising sea surface temperature, are of particular concern to large macroalgal habitats, and climate influenced decreases have already been observed in the USA and in Australia (Dayton et al. 1999; Edgar & Barrett 2000; Rogers-Bennett 2007; Rogers-Bennett et al. 2010).

Sedimentation also results in changes in sediment characteristics that may reduce suitability of habitats for species; in intertidal areas of estuaries, this typically results in muddier habitats and reductions in the abundance of seagrass meadows and intertidal shellfish beds, as well as facilitating colonisation by the mangrove *Avicennia marina* (Lundquist et al. 2014; Lovelock et al. 2015; Swales et al. 2015). For example, Suyadi et al. (2019) demonstrated correlations between mangrove expansion and catchment land-use and climatic variables (primarily temperature) during 1940–2014, resulting in an average of 3.2% increase in mangrove area and doubling of estuarine intertidal flats through estuarine infilling in the Auckland region. Direct mortality events from smothering by catastrophic sediment loads also occurs, affecting intertidal and shallow subtidal benthic species (Thrush et al. 2004, 2008) and the habitat forming species that are consumed or used by many coastal fisheries at some stages in their life history (Parsons et al. 2014, 2015; Morrison et al. 2014a, b). Anecdotally, pāua fishers report seeing more storm events, localised die-off of brown algae, increased sedimentation, and effects of acidification on pāua recruitment. If true, at least some of these changes are likely to be related to the effects of climate variability and point to the effects of climate change already being observed in New Zealand.

3.3 Ocean acidification

Considerable research is underway on the potential impacts of acidification on organisms in the New Zealand region, including some key fisheries species. Fisheries may be affected by ocean acidification (OA) through direct impacts on the organism itself (e.g., on development, growth, olfaction, sight, hearing), or indirectly via changes in their food supply or habitat (Branch et al. 2012). Current state-of-knowledge for ocean acidification specific to New Zealand was recently reviewed by Law et al. (2018a). The information that is most relevant to New Zealand fisheries from this review is reiterated and updated in this section.

Primary producers

For primary producers, studies to date of the impacts of OA on different phytoplankton groups in New Zealand waters have not identified significant changes in biomass, or community composition that would subsequently impact marine food webs (Law et al. 2018a). However, research into the impacts of OA on macroalgae (e.g., Connell et al. 2018) show differential responses related to species-specific variation in physiology and carbon source (Hepburn et al. 2011). Crustose coralline algae have been identified as one of the most vulnerable groups (Nelson 2009), with New Zealand crustose coralline algae exhibiting a reduction in calcification rates and growth under lower pH (Cornwall et al. 2014). Because crustose coralline algae provide both a settlement cue and a food source for pāua (*Haliotis iris)*, their decline or loss from coastal ecosystems may have repercussions for this fishery (e.g., Espinel-Velasco et al. 2020).

Calcifying organisms

Calcifying organisms, such as corals, sponges, sea urchins, gastropods, bivalves, and lobsters have been highlighted as particularly susceptible (e.g., Hepburn et al. 2011; Bell et al. 2013). Cold-water corals provide important biogenic habitat for fish and invertebrates on slope margins, ridges, and seamounts. A broad survey of the distribution of New Zealand cold-water coral species identified a strong dependency with the carbonate saturation state of deep waters (Tracey et al. 2013) and their vulnerability to the shoaling of the Aragonite Saturation Horizon (the depth at which the carbonate polymorph aragonite becomes undersaturated; when $\Omega_{Ar} < 1.0$). Many cold-water coral species can, however, tolerate some degree of aragonite undersaturation (Ω_{Ar} ~ 0.8–0.9), with some species found in areas of $\Omega_{Ar} = 0.7$ (Bostock et al. 2015). Experimental investigations of deep-water coral species, such as *Madrepora oculata* (found in New Zealand), revealed lower calcification rates and metabolic depression after 21 days under lower pH (-0.3 decrease to 7.76; Maier et al. 2009, Hennige et al. 2014). Respiration and growth rates of colonies of the dominant New Zealand species *Solenosmilia variabilis* maintained under ambient pH (7.88, $\Omega_{Ar} = 1.11$) and lower pH (7.65, $\Omega_{Ar} = 0.69$) showed no effect even after 12 months (Tracey et al. 2016; Gammon et al. 2018). However, their coenenchyme (the outer tissue that links the coral polyps and provides protection for the developing exoskeleton) was negatively affected (Gammon et al. 2018). Rock lobster (*Jasus edwardsii*) may also be affected by ocean acidification (Cornwall & Eddy 2015). Any changes to kina and rock lobster productivity may have wider consequences in coastal ecosystems, because these species often have important ecosystem roles (Pinkerton et al. 2008; Cornwall & Eddy 2015).

Experimental investigations of juvenile New Zealand pāua maintained under reduced pH conditions showed that although survival was not affected, growth was sometimes (Cunningham et al. 2016) but not always (Cummings et al. 2019) reduced. Dissolution of the shell surface was evident (Cunningham et al. 2016; Cummings et al. 2019), with thinning and thickening of different layers of the shell in lower pH conditions (Cummings et al. in 2019). Similar effects were found for growth and shell surfaces of flat oysters (*Tiostrea chilensis*) (Cummings et al. 2016b).

Targeted research to determine the ability of New Zealand pāua and green lipped mussels (*Perna canaliculus*) to acclimate and adapt to rising temperatures and acidification within the Coastal Acidification: Rates, Impacts and Management (CARIM) project, is concluding. Considerable impacts on pāua larval survival and development (Cummings et al. unpublished data) and on settlement (Espinel-Velasco et al. 2020) are indicated. Investigation into the impacts on early life stages of green lipped mussels in commercial hatchery tanks has shown that initial larval development and formation of the first shell (prodissoconch I), 24–48 h post-fertilisation, are severely impacted by extreme pH levels (pH 7.42; $\Omega_{Ar} = 0.80$), with all larvae exhibiting malformation or arrested development, and none surviving beyond veliger stage (N. Ragg, Cawthron, unpubl. data; Ragg et al. 2019; Law et al. 2018a). *Perna* larvae more than two days old showed greater resilience to this extreme low pH; shell growth and calcification decreased (Ericson 2010), and the survival rate was reduced by 60–85%, although the surviving larvae could metamorphose and recruit to the juvenile population. A dynamic energy budget model for *Perna* has indicated reduced growth, biomass, and reproductive output under projected ocean acidification (Ren et al. 2020).

Fish

It is currently unclear how fish species and stocks around New Zealand will respond to ocean acidification, because few empirical studies have been carried out. Recent tank experiments assessing the impact of elevated pCO_2 on yellowtail kingfish (*Seriola lalandi*) larvae demonstrated no effect on activity, growth, or survival, but did result in reduced swimming speed and distance moved in response to startle stimuli, and increased resting metabolism at elevated pCO_2 (Laubenstein et al. 2018; Watson et al. 2018; Jarrold et al. 2020). Examination of development of digestive organs in larval kingfish was not exacerbated by near-future ocean acidification and warming (Frommell et al. 2019). Similar experiments conducted on snapper (*Chrysophrys auratus*) suggested a range of both positive and negative effects of elevated pCO_2 on survival, distance moved from startle stimuli, aerobic scope, critical swimming speed, and hearing ability (McMahon et al. 2020a, 2020b). Early life history, growth, and survival (to 16 days old) was positively affected by elevated CO_2 (McMahon et al. 2020a). However, for juvenile snapper, elevated CO_2 had a negative effect on metabolic rates and swimming performance (more so than heatwave conditions), which could reduce their overall performance and potentially have consequences for population recruitment (McMahon et al. 2020b). A modelling assessment attempting to estimate the combined effect of elevated pCO_2 and temperature on snapper populations was unable to determine if this effect would be positive or negative, with sensitivities suggesting both increases and decreases in fisheries yield (Parsons et al. 2020).

Modelling-based studies of temperate New Zealand coastal ecosystems (Ecopath with an Ecosim ecosystem model for the Wellington south coast, including the Taputeranga Marine Reserve) suggest that fishing may have a larger effect on trophic group biomasses and trophic structure than ocean acidification; the effects of ocean acidification were only large in the absence of fishing (Cornwall & Eddy 2015).

4. EVALUATION OF FISHERIES AND ENVIRONMENTAL CHANGE — REVIEW OF NEW ZEALAND-SPECIFIC SPECIES INFORMATION

Seafood exports from both wild capture fisheries and aquaculture were worth more than NZ$2.0 billion to New Zealand's economy in 2018–19 (MPI 2019). Both in terms of value and volume of catches, New Zealand fisheries are dominated by bottom trawling. Of the wild-caught commercial catch, about 60% is finfish caught offshore by bottom trawls in waters deeper than about 250 m (MPI 2015a). New Zealand's commercial seafood catch varies from year to year, but typically comprises about 400 thousand tonnes per year (kilotonne per year; kt y^{-1}) of wild-caught finfish, 77 kt y^{-1} of invertebrates (80% squid), and 56 kt y^{-1} (meat weight) of aquacultured mussels and oysters (MPI 2015a, 2015b, Aquaculture NZ 2015). There are currently more than 100 species (or species groupings) in the New Zealand Quota Management System (QMS), and these species are divided into more than 600 separate stocks for management purposes. Total allowable commercial catch (TACC) limits are set for each stock. The New Zealand Fisheries Act (1996) also requires that TACCs should have "regard to the interdependence of stocks, the biological characteristics of the stock, and any environmental conditions affecting the stock".

Climate change effects on New Zealand fisheries are considered as part of an annual review of interactions between the seafood sector and the marine environment, called the 'Aquatic Environment and Biodiversity Annual Review' (Fisheries New Zealand 2020b). This review also includes a chapter on trophic and system-level effects that are potentially relevant to managing New Zealand fisheries. A strategic approach 'Fisheries 2030' specifies a single goal for the New Zealand fisheries sector, which is to have "*New Zealanders maximising benefits from the use of fisheries within environmental limits*" (Ministry of Fisheries 2009). To support the goal, Fisheries 2030 includes the desired environment outcome, that "*The capacity and integrity of the aquatic environment, habitats and species are sustained at levels that provide for current and future use, including:*

- *biodiversity and the function of ecological systems, including trophic linkages are conserved*
- *habitats of special significance to fisheries are protected*
- *adverse effects on protected species are reduced or avoided*
- *impacts, including cumulative impacts, of activities on land, air or water on aquatic ecosystems are addressed.*"

Clearly, investigations of how climate change might impact each and all of the 130 commercially exploited marine species in New Zealand waters are desirable to meet government requirements but would be impractical (due to lack of data and financial constraints). Therefore, this project has identified a smaller subset of key species and species groups that are most important to New Zealand and New Zealanders from economic, social, cultural, and ecological perspectives as well as data availability. A similar combined qualitative/quantitative assessment approach to identifying key species has been used elsewhere (e.g., for fish and shellfish vulnerability to climate change in the USA; Morrison et al. 2015; Hare et al. 2016).

Economic importance can be judged in terms of annual export values or total asset values. The catching sectors in the New Zealand commercial fishery are separated relatively clearly into offshore (generally deepwater) and inshore fleets. For social and economic reasons, the most important species for these two catching sectors (identified by examination of total catch tonnages) have been included in this review. Similarly, estimates of total recreational catches indicate species with high social importance. It was also apparent that species of high cultural importance to Māori (Leach & Boocock 1993) were often the same as the important recreational species. Table 2 lists the 32 species (or species groups) that were identified as being the most important. The wild-caught species together account for about 75% of the total commercial fishery catch, whereas the two aquaculture species highlighted contribute substantially to economic returns.

Species groups are arranged under five categories:

1. Shellfish (wild-caught and aquaculture),
2. Fish aquaculture (salmon),
3. Inshore (the area of coastal fringes and shelves primarily shallower than 250 m),
4. Middle depths/Deepwater (primarily the shelf edges and slopes deeper than 250 m),
5. Oceanic (highly migratory species with distributions well beyond the New Zealand EEZ).

Appendix 1 summarises the state of knowledge for each of the 32 selected species groups with respect to aspects that may be impacted by climate change (e.g., their geographical distribution, preferred depth and water temperature ranges, main dietary components). MPI Plenary documents helped inform the species reviews — the 2014 November Plenary (MPI 2014), the 2016 May and November Plenaries (MPI 2016b, c), and the May 2017 Plenary (MPI 2017). The primary research literature and non-published reports were also canvased for the species-by-species evaluations.

For example, the preferred water depth and water temperature ranges for selected species groups are shown in Figure 8. These preferences, for 27 of the 32 fish species groups (shellfish and some oceanic tunas excluded), were estimated using data from the MPI *trawl* research database, which holds all information related to fishery surveys around New Zealand. Most of the data are from trawl tows, but some information from surveys using fish pots or baited lines are also included. Note that these data may not comprehensively describe the depth and temperature distributions of the species, because they contain only information from locations and times where research surveys have been conducted. There are areas that are sparsely surveyed, e.g., around northern North Island, and areas deeper than 800 m in much of the New Zealand region. The catch records comprising both the 2.5% deepest and 2.5% shallowest were omitted from the dataset in an attempt to exclude data reporting errors. Similar pruning was done for the warmest and coolest water temperature records. Thus, there is a focus on the bulk of the distribution of the fish catches. Although changes at the ‘extremes’ are of interest, they may not all be well determined. For example, although the southern limit of a more northern and ‘warm water’ species may be well determined around New Zealand, the northern limit may not be described by these data if the species extends into warmer waters to the north of New Zealand’s EEZ.

This knowledge provided the basis on which to evaluate whether these species might be affected by changes expected in properties of the oceanic and coastal waters over the remainder of this century. All these species are virtually certain to be impacted in some way by any environmental change that alters water temperatures, water chemistry, or the behaviour of currents. Effects could be direct (e.g., result from a change that affects survival or functioning of the organism) or indirect (e.g., in response to climate change induced alteration of the abundance or availability of preferred prey).

The extensive information presented in Appendix 1 is summarised below from two perspectives. Firstly (Section 4.1), the state of knowledge of species characteristics (e.g., distribution, survival) with respect to the environmental parameters anticipated to change (e.g., temperature, salinity). Secondly (Section 4.2), the implications of environmental change to the species groups with a focus on stock assessment parameters. The latter approach was used to link the potential of climate change-fisheries interactions with the parameters used in stock assessment models (i.e., key parameters which determine population dynamics, such as survival and recruitment), and this approach was considered more appropriate and useful than an evaluation based only on climate change drivers which are not managed.

Table 2: The 32 species or species groups judged to be the most important to include in an investigation of climate and ocean change effects, and/or appropriate representatives of a habitat type. Reported or estimated landings (t)[1,2] of each group is also provided. For summaries of the state of knowledge of how each of these selected species groups may be impacted by climate-related changes, see Appendix 1.

Species groups	Commercial catch (t)[1]	Recreational catch (t)[2]
Shellfish (wild-caught; aquaculture)		
Green lipped mussels	99 716*	–
Flat oyster[#]	13 200 000**	185 230**
Pāua[#]	956	123
Fish aquaculture		
Salmon	–	–
Inshore		
Snapper[#]	6 232	4 567 (can fluctuate from 3000–4500)
Tarakihi	6 038	223
Red gurnard	3 910	195
Red cod#	3 804	308
Rock lobster#	2 816	209
Blue cod#	2 198	302
Kahawai#	2 181	1 785
Rig[#]	1 413	6
Elephant fish	1 340	–
John dory[#]	652	39
Middle depths / Deepwater		
Hoki	156 500	–
Jack mackerels	48 262	–
Southern blue whiting	31 887	–
Barracouta#	24 327	85
Arrow squid	16 310	–
Ling	15 002	~15–40
Oreos***	11 059	–
Silver warehou	9 053	–
Hake	8 248	–
Orange roughy	8 215	–
Dark ghost shark	1 283	–
Scampi	974	–
Oceanic		
School shark#	3 110	200 t in 2000 (or 22 901 indiv. from 2012)
Albacore tuna#	2 537	92
Southern bluefin tuna	929	–
Blue shark	142	–
Pacific bluefin tuna	17	–

[1]Average annual reported commercial landings in most recent years (from MPI 2016b, c, 2017); includes the 10 most caught offshore, and 4 most caught inshore species groups.
[2]Estimated annual recreational catch (derived from MPI 2016, 2017). The Plenary documents state that there are often inaccuracies for some recreational harvest figures and some estimates could be implausibly high/low.
[#]Species considered culturally important to Māori (from Leach & Boocock 1993).
*Green lipped mussels reported as whole weight, data source: Aquaculture NZ (2017).
**Flat oysters are reported as numbers.
***Smooth Oreos and black Oreos are combined in this table but are discussed separately elsewhere in this report.

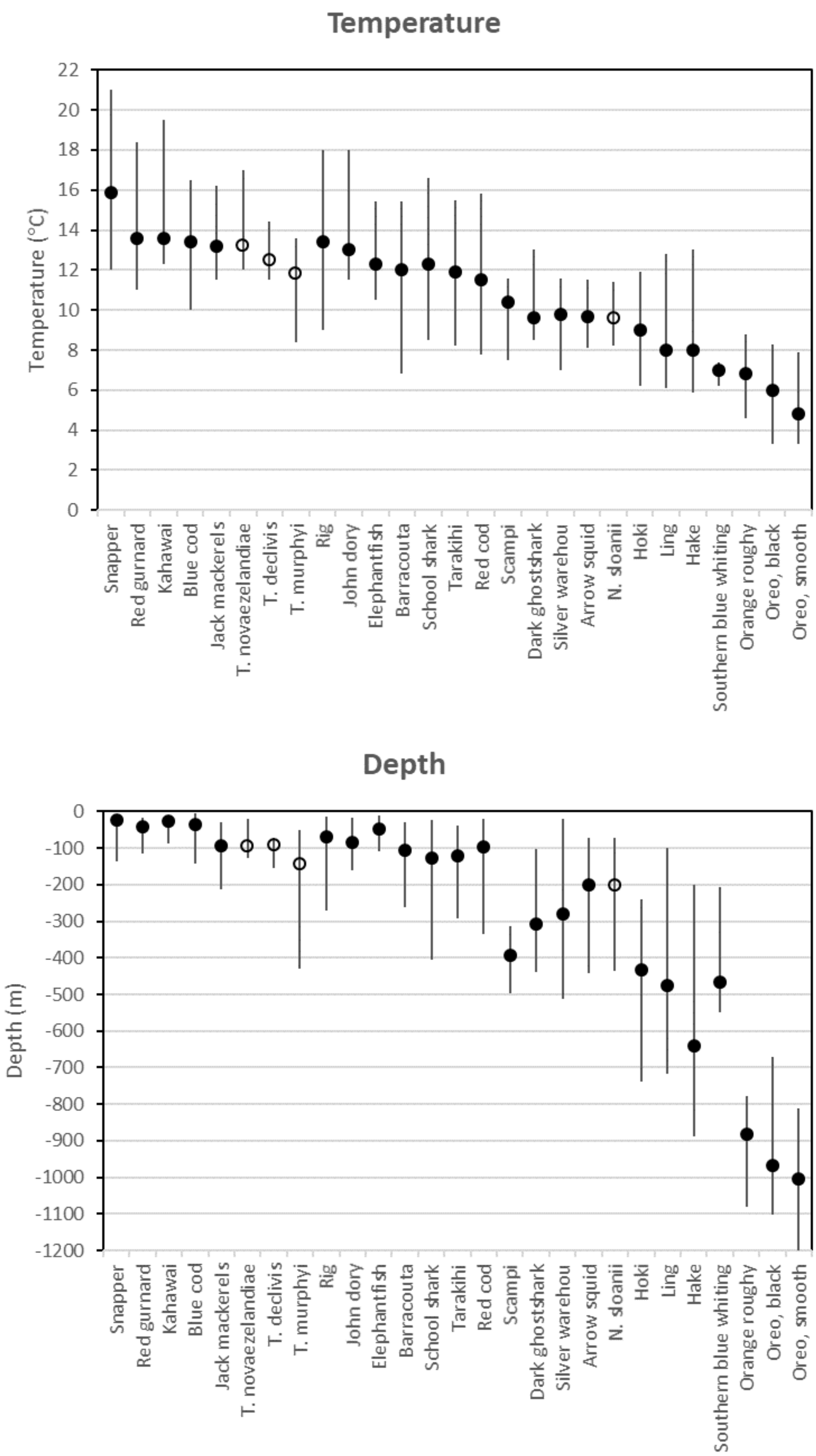


Figure 8: Seafloor temperature and depth ranges for key fisheries species recorded in the *trawl* research database up to the end of 2015. Plots are the median temperature or bottom depth at the mid-point of all recorded catches summed (solid circle) ± 47.5% of the recorded catch by weight. Species have been ordered along the x-axis from highest to lowest temperature (top figure) and shallowest to deepest depth (bottom figure). Data for jack mackerels are as a total, and separately for the three main species (*T.* for *Trachurus*, the latter have open circles for the mid-points). Similarly, arrow squid are a presented as a grouping, and separately for the single species *N. sloani* (open circle). Green-lipped mussels, flat oyster, pāua, rock lobster, blue shark, and the three tuna species are not included.

4.1 Key New Zealand fisheries species – comment on potential climate and ocean change impacts

Table 3 indicates whether changes in key environmental parameters potentially affected by climate and ocean change might impact the 32 species groups. The majority of potential impacts on these species will come from changes in temperature or from ocean acidification.

Species were considered potentially sensitive to temperature change if they were caught within a very narrow temperature range (e.g., arrow squid), or where growth, distribution, or spawning patterns are known to be correlated with temperature (e.g., tarakihi). Ocean acidification sensitivity was primarily considered to be an indirect impact, through influence on biogenic habitat or prey items. However, for some species acidification may have a direct effect. For example, it has been shown to weaken the byssal thread attachment in some species of *Mytilus* mussels (O'Donnell et al. 2013; Zhao et al. 2017) but not in *M. edulis* (Clements et al. 2018; Dickey et al. 2018); there is no information available on the byssus of *Perna canaliculus*. Ocean acidification clearly affects early development of molluscs and echinoderms (Kroeker et al. 2013) by reducing the integrity of their shells/skeletons (e.g., Clark et al. 2009). The impacts on fish species was considered to depend primarily upon the component of these prey items in their diet. Recent work has indicated sublethal, interactive effects of temperature and acidification on larval kingfish (Laubenstein et al. 2018), and it has been postulated that distribution of habitat forming deep-sea corals may indirectly affect the future distribution of deep-sea fish that utilise these habitats (Law et al. 2018a). Species affected by coastal erosion and sedimentation indicated a dependence on coastal habitats for at least some part of their life cycle.

The many question marks in Table 3 are indicate the lack of available data with which to evaluate the potential impacts of environmental change, rather than an absence of an effect on that species. These unknowns could be because of an as-yet incomplete understanding of the physical change (e.g., shifting of fronts, magnitude of warming) and/or the biological response of the species. One important observation is that there is seldom a good understanding of the life habits of a species available across its entire life cycle; although fisheries information provides data on distributions of the larger and older size classes commonly caught by fisheries, there is relatively little knowledge of smaller and early life history stages which may be more susceptible to changing environmental conditions. The notable exceptions to this are the shellfish species, which have been relatively well studied.

Basic information on geographical distribution is also included in Table 3. The distribution boundaries (the edges of the species' current distribution within the New Zealand EEZ) were identified from visual examination of the National Aquatic Biodiversity Information System (NABIS), where clear edges occur. It is assumed that a species response to climate change would be greatest at the edges of its range, where it may more often encounter unfavourable conditions (e.g., kingfish appearing in greater numbers than previously in southern New Zealand). Where a climate influence on a species is known or highly likely (shown as a tick in Table 3), these areas indicate where a response might first be expected. For example, climate change might influence species distribution and/or population dynamics around the top of the South Island, most obviously in snapper, kahawai, John dory, and hake. Greater change might be expected for those species which occur in relatively narrow temperature ranges; these are southern blue whiting, squid, jack mackerels, and some deepwater species (although a small temperature range observed for deepwater species like orange roughy may be more a function of habitat stability, rather than the temperature tolerances of the species).

Other useful indicators of both species and regional risk might consider species longevity, where the hypothesis would test if the total biomass of short-lived species would show responses to climate influences on their distribution and dynamics faster than long-lived species.

Table 3: A summary of environmental factors that are likely to change with on-going climate change, showing those which will potentially affect the 32 species groups. Note that the impacts indicated here could be positive or negative. For further information on the impacts, see the 'Climate change challenges' in the species summary text below. ✓ evidence of likely impact; ~ belief that an impact will occur; ? no available information to postulate an impact. N: north; W: west; E: east; S: south; C: coast; NI: North Island; SI: South Island; – no edges discernible.

Species or species group	Water temperature	Water stratification/ masses	Water circulation	Ocean acidification	Coastal erosion & sedimentation	Oxygen concentration	Salinity	Distribution boundaries
Shellfish (wild-caught; aquaculture)								
Flat oyster	✓	?	?	✓	~	?	?	–
Green lipped mussel	✓	?	?	✓	✓	?	?	–
Pāua	✓	?	?	✓	~	?	?	–
Fish Aquaculture								
Salmon	✓	?	?	?	?	?	?	–
Inshore								
Blue cod	?	?	?	?	✓	?	?	NWNI
Elephant fish	✓	?	~	?	?	?	?	WCSI, SSI
John dory	✓	?	?	?	?	?	?	NSI
Kahawai	?	?	?	?	✓	?	?	NSI
Red cod	✓	?	?	?	?	?	?	NNI
Red gurnard	✓	?	✓	?	?	?	?	–
Rig	~	?	?	~	~	?	?	–
Rock lobster	?	?	✓	✓	?	?	?	–
Snapper	✓	?	?	~	✓	?	?	NWSI, ECNI
Tarakihi	✓	?	?	~	?	?	?	–
Middle depths / Deepwater								
Arrow squid	✓	?	?	?	?	?	?	WCSI, ECNI
Barracouta	?	?	?	~	?	?	?	–
Hake	✓	?	~	?	?	?	?	SNI
Hoki	✓	?	~	?	?	?	?	WCNI
Jack mackerels	~	?	?	~	?	?	?	–
Ling	?	?	?	?	?	?	?	–
Orange roughy	~	?	~	?	?	?	?	–
Oreo, black	?	?	~	?	?	?	?	SENI, SWSI
Oreo, smooth	?	?	✓	?	?	?	?	WCSI, SENI
Scampi	✓	?	?	~	?	?	?	Patchy
Shark, dark ghost	~	?	?	?	?	?	?	ECNI, NWNI
Silver warehou	?	?	?	?	?	?	?	SWSI
Southern blue whiting	✓	✓	?	~	?	?	?	SSI
Oceanic								
Albacore	✓	~	~	~	?	?	?	ECNI, SWSI
Bluefin, Pacific	✓	?	?	~	?	?	?	SENI, ESI
Bluefin, Southern	?	?	?	~	?	?	?	ECNI, SSI
Shark, blue	✓	?	?	?	?	?	?	–
Shark, school	✓	?	?	?	?	?	?	–

4.2 Key New Zealand fisheries species – comment on quantitative fisheries advice

This section provides an evaluation of the implications of environmental change to the 32 fisheries species below, with a focus on stock assessment parameters. A summary of aspects of a species' biology that are implicitly or explicitly modelled in demographic stock assessments and could be impacted by climate change (either negatively or positively), is presented in Table 4. The table column headings refer to key biological processes in population assessment models, plus parameters related to the availability of the species to surveys or to the fishery (i.e., the catchability, *q*, values). The information was derived from a combination of published reports (see Appendix 1), and by expert opinion (including, M. Dunn, M. Francis, P. Horn, K. Michael, D. Tracey, I. Tuck, V. Cummings).

In a simple stock assessment model such as the production (surplus yield, or Graham-Schaeffer) model, the yield from a fish stock is determined by two parameters, one describing pre-fishery population size (carrying capacity) and one describing the intrinsic population growth rate, with an implicit assumption that the model is applied to a discrete population (stock). When a stock is modelled using more complex demographic models, as is often done in New Zealand stock assessments, more parameters describing more detailed processes are required, and typically include individual growth (in length and weight), maturity at length or age, the relationship between spawning stock and subsequent recruitment, natural mortality rate, selectivity to surveys and fisheries, and (when assumed) migrations. There are also parameters associated with model fitting to data sets, in particular the availability of the fish to surveys, and to fisheries (catchability, *q*) that are assumed to be constant. For example, for mussels, sea level rises and changes to exposure may change available habitat and therefore the *q*, the proportion of habitat available, is decreasing. When based on expert opinion, it seemed likely that all the assessment model parameters could be influenced to some extent by changes in environmental conditions (Pinkerton et al. 2018). However, actual evidence for impacts (or no impact) is sparse and identifying them may be confounded with the density dependent responses expected following population depletion (i.e., lower natural mortality, faster growth, earlier maturation, and higher fecundity might all be expected as density dependent responses). Where long-term change in key productivity parameters for a fish stock can be identified, taking these trends into account when projecting future yield may help address the effects of climate change on stock productivity (Pinkerton et al. 2018).

For some species, the likely impacts of climate change are unknown (e.g., kahawai, tarakihi), whereas for others there is information on several parameters (e.g., pāua, snapper). Evidence for climate effects is most extensive for inshore shellfish species. For offshore species information is sparse: for hoki there are known changes in growth rate over time (Ballara & O'Driscoll 2017), the cause of which is unknown but is most likely related to density dependence; hake may have switched prey in response to low hoki density (Horn & Dunn 2010), and there is a suspected shift in availability of hoki to the surveys and fishery in the Subantarctic, which has been hypothesised to be a response to environmental change (McKenzie 2017). However, in the Subantarctic, changes were reported to a number of ecosystem components (predators, prey, and competitors of hoki) during anomalously warm and cold years in the 2000s; as such, specific links to hoki biomass remain unclear (O'Driscoll et al. 2015). Similarly, correlations between ocean climate and levels of hoki recruitment currently remain equivocal (Bull & Livingston 2001; Francis et al. 2006). Hoki spawning success (i.e., feeding success of newly hatched larvae) could however be impacted by ocean climate (Murdoch 1990). Research underway using the Chatham Rise Atlantis ecosystem model has suggested some trends in stock abundance (for hoki and others), which is estimated in stock assessment models to be due to trends in recruitment, but may alternatively be due to trends in natural mortality rate brought about by ecosystem changes. For example, the stock assessment for hoki estimated that recruitment was relatively high during the 1980s to 1990s and relatively low since the mid-1990s, resulting in a steep biomass decline and then recovering and indicating a roughly flat biomass trajectory (Fisheries New Zealand 2020a). The Atlantis model reproduced a similar biomass trajectory, with recruitment being constant throughout but allowing temporal changes in natural mortality rate (McGregor et al. 2019). This latter observation requires further research but suggests it may be misleading to search for environmental impacts on recruitment without also considering species interactions.

For several other species in Table 3, all available information is derived from the study by Dunn et al. (2009); e.g., school shark migrations and availability, red gurnard availability. That report found correlations were more common between environment and species occurrence (distribution), than between environment and population dynamics (e.g., growth, recruitment). Correlations only were identified by Dunn et al. (2009); no causation was examined in any species. It is also worth noting that the species list excluded species such as gemfish, for which a strong correlation of recruitment and ocean climate variables was found (Renwick et al. 1998).

For most species, climate impacts remain unknown and can only be speculated. General hypotheses for impacts follow a large body of research showing that environment directly influences physiological processes, (e.g., growth, maturation, swimming speed, and other behaviours), and in concert these influence processes such as natural mortality rate, distributions, and availability to fishing (e.g., Roessig et al. 2004; Portner et al. 2010; Morley et al. 2018; there is a very large literature on this subject which is not compiled here). Additionally, productivity and distribution of prey items (particularly zooplankton) are likely to be more directly influenced by ocean climate, with consequences to the distribution and productivity of the fish species. Although wild-caught mobile species are able to move in response to adverse conditions, and thereby mitigate environmental changes (Dulvy et al. 2008), constrained species such as sessile shellfish, or caged species such as salmon, are less able to move and can be adversely and dramatically impacted (e.g., "*Hotter-than-normal water kills off salmon in the Sounds*", www.stuff.co.nz, 2 Feb 2018; Salinger et al. 2019).

Little or no information on climate impacts was available for deepwater species. The environment for deepwater species is relatively stable, and temperature may change relatively little at these depths in the future. Therefore, it could be assumed that little will change for deepwater species. However, deepwater species will be the first to be exposed to the effects of increasing ocean acidity. If the carbonate saturation horizon was to rise to around 300 m (this is plausible), this would most likely have dramatic impacts on the survival and productivity of heavily calcified species, such as scampi, and potentially all deepwater species that use coral habitat. Some major impacts of climate change are therefore expected in deep-sea ecosystems (Sweetman et al. 2017).

One potential impact on availability of fisheries in deep waters, particularly those at more southern latitudes, is that future climate change could produce more extreme weather events, e.g., more frequent and stronger storms (Law et al. 2018b). Such a change could reduce the opportunities for vessels to fish. It could impact even the deepest fisheries; Taylor (2001) found that a wind speed predictor was significant in Subantarctic orange roughy standardised CPUE models.

Table 4 summarises, for each species, the biological characteristics (see Appendix 1) that could potentially be affected by predicted change in the various environmental parameters from a population dynamics perspective. However, there is no attempt to evaluate which parameters might be most influenced by environmental change, and most influential in determining future stock productivity, assessment, and management. Therefore, for example, changes in natural mortality rate (and subsequent recruitment) might be expected to have a more profound effect than changes in growth, such suppositions have not yet been evaluated. Parameters may be correlated (e.g., growth and mortality, assuming size-dependent mortality). In addition, this summary does indicate whether a suggested change might be positive or negative. If climate change is considered to not have an effect (as marked by '×' in Table 4), this may reflect either no statistically significant effects being determined to date, OR, a reflection of inadequate understanding of how it works and how stocks interact. Note that a published hypothesis of climate-induced changes is not considered here to be an effect in the absence of data, i.e., without directed and quantitative analyses that test the hypothesis. For example, although a hypothesis has been presented that John dory extended their range down the west coast of the South Island in response to warmer temperatures (Dunn & Jones 2013), this study's authors are not aware of any quantitative data analyses that test and support this hypothesis (hence only *a change is suspected*).

Further discussions are required with Fisheries New Zealand should this stock assessment parameter approach be considered a promising way to evaluate species responses to anticipated environmental change. These discussions could include, for example, consideration of the scope of "stocks" in Table 4; given that within the EEZ, stocks differ considerably among species (from multiple stocks to a single large stock), the evaluation of the stock, migration, availability to survey, and availability to fisheries are also affected.

Table 4: A summary of biological characteristics that describe species' population dynamics that could potentially be affected by predicted change in the various environmental parameters discussed in this report over the following decades. Symbols in the cells denote: there is published information indicating climate *will not* have an effect (×); there is published information suggesting climate *will* have an effect (✓); there are no available data, but a change is suspected from expert opinion (~); the expert group was unable to find any information, or to reach any conclusion (?). Note that any changes indicated here could be positive or negative. For sessile species, migration is interpreted as changes in circulation and spat fall. The information on the individual species that supports this table can be found in Appendix 1. (Continued on next page)

Species or species group	Stocks (number and/or extent)	Growth (length-at-age, weight-at-length)	Maturation and spawning	Natural mortality rate	Recruitment (mean and/or variability)	Migrations	Availability to surveys	Availability to fisheries
Shellfish (wild-caught; aquaculture)								
Flat oyster	?	✓	✓	✓	✓	×	×	?
Green lipped mussel	?	✓	✓	✓	✓	?	?	?
Pāua	✓	✓	✓	✓	✓	×	?	✓
Fish Aquaculture								
Salmon	✓	~	~	✓	~	×	×	~
Inshore								
Blue cod	~	~	~	?	?	×	?	?
Elephant fish	~	~	~	~	~	~	~	~
John dory	~	~	~	~	~	~	~	~
Kahawai	~	~	~	~	~	~	~	~
Red cod	~	~	~	~	✓	~	~	~
Red gurnard	~	~	~	~	~	~	~	~
Rig	~	~	~	~	~	~	~	~
Rock lobster	?	✓	?	?	✓	✓	✓	✓
Snapper	~	✓	✓	~	✓	~	~	~
Tarakihi	~	~	~	~	~	~	~	~
Middle depths / Deepwater								
Arrow squid	~	~	~	~	~	~	~	~
Barracouta	~	~	~	~	~	~	~	~
Hake	~	~	~	~	✓	~	~	~
Hoki	~	~	~	~	✓	~	✓	~
Jack mackerels	~	~	~	~	~	~	~	~
Ling	~	~	~	~	~	~	~	~
Orange roughy	~	~	~	~	~	~	~	✓
Oreo, black	~	~	~	~	~	~	~	~
Oreo, smooth	~	~	~	~	~	~	~	~

Species or species group	Stocks (number and/or extent)	Growth (length-at-age, weight-at-length)	Maturation and spawning	Natural mortality rate	Recruitment (mean and/or variability)	Migrations	Availability to surveys	Availability to fisheries
Scampi	~	~	~	~	~	×	~	~
Shark, Dark ghost	~	~	~	~	~	~	~	~
Silver warehou	~	~	~	~	~	~	~	~
Southern blue whiting	~	~	~	~	✓	~	~	~
Oceanic								
Albacore	×	~	~	~	~	✓	~	✓
Bluefin tuna, Southern	×	~	~	~	~	~	~	~
Bluefin tuna, Pacific	~	~	~	~	~	~	~	~
Shark, blue	×	~	~	~	~	~	~	~
Shark, school	×	~	~	~	~	~	~	~

4.3 Estimating fish distribution under climate change: preliminary investigation of the use of a statistical spatial population model and remotely sensed environmental data

Appendix 2 presents an example investigation to predict a fish species distribution and environmental preference using a statistical spatial population model (SPM). Using albacore tuna as a model species, a statistical spatially-explicit population model was used for the New Zealand region to estimate their environmental preferences, and to predict their relative spatial distribution (areas of relatively high and low abundance). The model parameters describing environmental preferences were estimated using remote-sensed environmental data (sea surface temperature, net primary productivity) and fish abundance as inferred from commercial fishery catch rates. The model estimated that albacore preferred waters with a sea surface temperature greater than 16 °C and net primary productivity greater than 573 mg C m^{-2} d^{-1}. The estimated temperature preference was consistent with previous studies (Christian & Holmes 2016).

There have been two main fishery areas for albacore tuna. The model explained the distribution of the relatively large fishery to the northeast of New Zealand reasonably well but explained the fishery to the southwest of New Zealand less well. The model correctly (to the best of knowledge) predicted the absence of albacore from most New Zealand waters during the winter and spring, and the absence of albacore from Chatham Rise.

Under climate change scenarios, the model predicted that the available habitat for albacore in New Zealand waters would become much more extensive and would shift about two degrees latitude further south. Further, it predicted that albacore would become available for capture around northern New Zealand throughout the year and would have a preference for Chatham Rise during the autumn.

The statistical estimation of parameters for spatially and temporally explicit models requires good and numerous data. Poor model convergence was encountered, and multiple model runs were required to achieve the best fits to data. However, the most intensive tasks were data compilation and grooming. Once data were collated and compiled, the actual model runs were relatively straightforward.

The Spatial Population Model software used here was useful in simulating and understanding a fish species' distribution. However, additional and more relevant, good quality, and consistent data would improve the veracity of future research efforts. Results from this preliminary study were promising, and with some further investigation and development, results and insight from this approach could be improved for the species most likely to show distributional changes in response to environmental conditions.

5. ASSESSMENT TOOLS TO EVALUATE RISKS AND EXPLORE ADAPTATION OPTIONS

A key aim of this project was to ensure the technical information presented in Chapters 2, 3, and 4 was of use to fisheries management and policy, and the fisheries community. Another aim was to take the largely literature-based assessments of New Zealand fisheries a step further, to highlight species vulnerabilities and begin to assess mitigation and adaptation options.

This involved workshops with fishers, managers, and scientists, initially to brainstorm the issues and needs, including user-friendly assessment tools, and subsequently, to evaluate vulnerabilities for specific fisheries species using internationally proven risk assessments. These workshops were facilitated by internationally recognised climate adaptation specialists Lara Hansen and Eric Mielbrecht from EcoAdapt, who have developed a number of decision support tools with government agencies in the USA, Canada, and Australia.

A day-long workshop, held in November 2016, was attended by 27 people (industry and central government representatives, scientific experts) with interest in contributing to the project objective of identifying risks and opportunities that are likely to arise for the seafood sector as a consequence of future environmental change in coastal and offshore New Zealand waters (Appendix 3). In general, workshop participants agreed that the incorporation of climate change into fisheries sector strategic planning and management was overdue, and that a number of entry points existed whereby this could occur. However, for some sectors, increasing the profile of climate change and potential implications for New Zealand fisheries within decision making was required, because climate change was not currently a high priority for all groups. Key information gains through better linkages with research funded by other organisations (i.e., awareness of climate change research commissioned by other central government agencies, and aligned research funded by MBIE and Marsden), improved awareness of the relevance of many physical drivers to fisheries, and the potential for new analyses of fisheries information specific to climate change could all potentially enhance the adaptation potential of New Zealand fisheries. Additionally, key ‘entry points’ (e.g., Figure 9) were suggested through individual fishery stock assessments; points where addition of climate change drivers to the assessments could help predict the influence of these drivers on fish stocks. Incorporation of climate change into Fisheries sector 5-year plans, and prioritisation of filling information gaps to inform Fishery Research Plans, were some of the examples discussed.

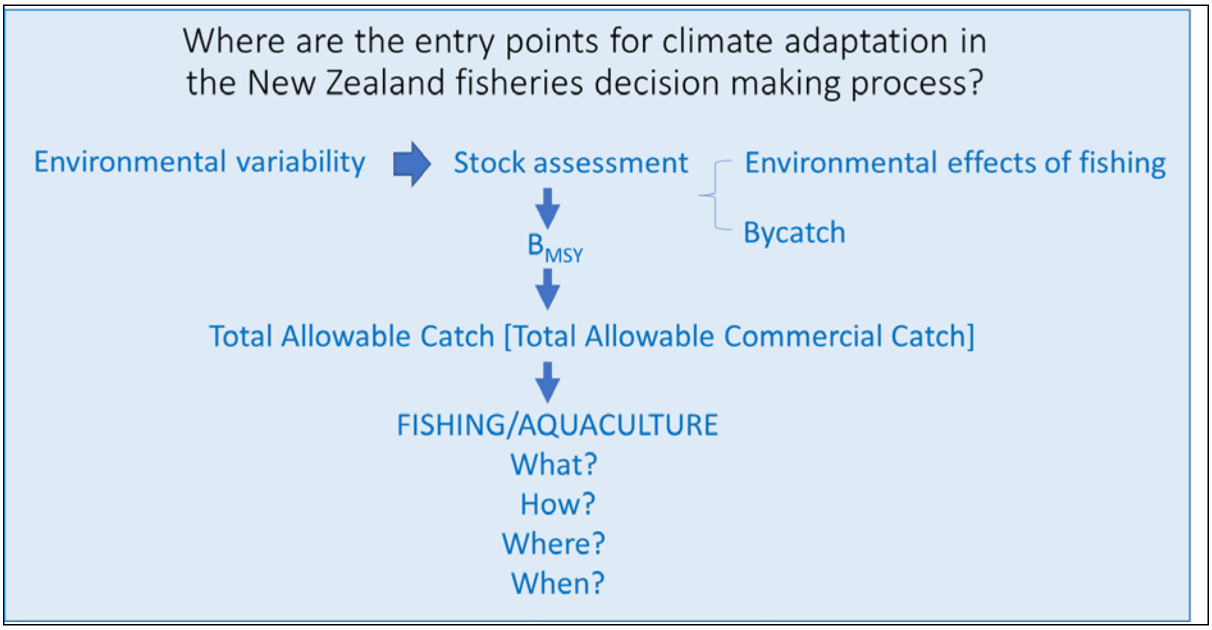


Figure 9: Current process to identify potential entry points for decision making in the fisheries and aquaculture industry in New Zealand. B_{MSY} is the spawning stock biomass at maximum sustainable yield.

A range of decision support tools used overseas to disseminate the state of knowledge of information on climate change were introduced (e.g., Hansen et al. 2017). A suite of available templates that could be built upon in a New Zealand context to evaluate risk and adaptation/mitigation options was discussed. These were subsequently developed and trialled for three selected New Zealand species (hoki, snapper, and pāua), as described below.

5.1 Decision support tools – evaluations using three species

The 'species summaries' tools were selected by workshop participants and the MPI project team as particularly useful in a New Zealand context. Although ideally, these would have been generated for all 32 species explored in Chapter 3, this was neither practicable from a time perspective, nor possible due to the lack of information on how many of these species were influenced by the environmental parameters likely to be affected by climate change (Tables 3 and 4). Three species were selected for which relatively good information was available (determined in Chapter 3): pāua (shellfish), snapper (inshore), and hoki (middle depths/deepwater). Building on the information for these species summarised in Chapter 3 and Appendix 1, individual summaries were developed in a 'report card' framework. This was achieved using a series of iterative workshops and focus groups, involving fishers, managers, and scientists with knowledge of these three species. Once species vulnerability assessments were completed by considering the sensitivity, exposure, and adaptive capacity of each species and fishery, brief synopses of this vulnerability and some potential options to reduce vulnerability were summarised in the report card framework.

The tools were trialled at three species-based workshops in November 2018 (shellfish – pāua; inshore – snapper; deepwater – hoki) with key individuals suggested by MPI who could contribute information that reflects both fisher and resource manager knowledge, and that incorporates management and fisher behavioural options that could be used as future climate adaptation strategies. These tools were designed to provide information on:

- the key implications of climate change for the selected fishery, including potential interactions with non-climate stressors;
- potential mitigation, response and adaptation actions that can improve fishery outcomes in the face of environmental change;
- relevant resources and tools that the fisheries community can use to make climate-informed decisions on a regular basis.

The tools for each species were updated following input at a workshop for each species, and further iterations occurred with workshop attendees to form a final 'report card'. A final step included the NOAA Rapid Vulnerability Assessment (Morrison et al. 2015; Hare et al. 2016), whereby either individuals or small groups were taken through a process of assessing individual fisheries sensitivity to climate change for selected parameters and for exposure of each species to a suite of climate variables (Table 5). This methodology was developed by NOAA (USA) to assess the vulnerability of marine fish and shellfish species to a changing climate. It leverages existing knowledge from both published sources and expert opinion to generate transparent, easily understood outputs that will provide insight into which species are likely to be the most vulnerable to decreases in abundance due to climate change and identify the key drivers behind the vulnerability. In this assessment, twelve sensitivity attributes of each fishery are assessed (Table 5) and the exposure component is divided into a number of exposure factors (Table 5), with scores calculated to represent both the attribute score and the data quality to support assessment of that attribute (Table 6).

Final scores for the Rapid Vulnerability Assessment are calculated as: Very High, High, Moderate, or Low, using a matrix to combine the sensitivity and exposure attribute scores. For sensitivity and exposure attributes a logic rule was applied to determine scores: Very High, if 3 or more mean attribute or factor scores are greater than 3.5; High if 2 or more attribute of factor scores are greater than 3.0; Moderate if 2 or more mean attribute or factor scores are greater than 2.5; or Low if less than

2 or more mean attribute or factor scores are greater than 2.5 (Morrison et al. 2015; Hare et al. 2016). For example, in the pāua assessment, the sensitivity score was Very High (three sensitivity attributes scoring greater than 3.5) and the exposure score was Very High (five exposure attributes scored greater than 3.5), making the total vulnerability score, according to the matrix, Very High. In the snapper assessment, the sensitivity score was High (three sensitivity attributes scoring greater than 3) and the exposure score was Moderate (two exposure attributes scored greater than 2.5), making the total vulnerability score, according to the matrix, Moderate.

These Rapid Vulnerability Assessment scores for each of the three species were integrated into the Species summary report cards. The final assessment of each species is presented in a two-sided A3 report card, with species descriptions and summaries of known and likely responses to future climate change on the first side, and mitigation, response, and adaptation actions that could improve fishery outcomes in the face of climate change that were identified on the second side. The mitigation/response/adaptation options include a rating of the feasibility of implementing each option, and of the effectiveness of the option if it were able to be successfully implemented. Species summaries for pāua (shellfish), snapper (inshore), and hoki (middle depths/deepwater) are presented in Figures 10, 11, and 12, respectively.

Table 5: A summary of the 12 sensitivity attributes and 10 exposure attributes, including the goal of the attribute and brief descriptions of what would be considered a low and a high score based on Morrison et al. (2015). Each attribute is scored as 1 = Low, 2 = Moderate, 3 = High, 4 = Very high. (Continued on next page)

Sensitivity attribute	Goal	Low score means	High score means
Stock Size/Status	To determine if the stock's resilience is compromised due to low abundance	High abundance	Low abundance
Other Stressors	To account for other factors that could limit population responses to climate change	Low levels of other stressors	High levels of other stressors
Population Growth Rate	Estimate the productivity of a stock	High productivity	Low productivity
Complexity in Reproductive Strategy	Identify reproductive strategy that may be disrupted by climate change	Low complexity	High complexity
Spawning Cycle	Identify spawning strategies that are more sensitive to changes	Year round spawners	Short duration aggregate spawners
Early Life History Survival and Settlement Requirements	Determine the relative importance of early life history requirements of a stock	Larval requirements are relatively resistant to environmental change	Larval requirements are specific and likely to be adversely impacted by environmental change
Sensitivity to Ocean Acidification	Determine the stock's relationship to "sensitive taxa" (including its own sensitivity)	Is not a sensitive taxon and does not rely on a sensitive taxon for food or shelter	Stock is a sensitive taxon
Habitat Specificity	Determine the relative dependence a stock has on habitat and the abundance of the habitat	Habitat generalist with abundant habitat available	Habitat specialist on a limited habitat type
Prey Specificity	Determine if the stock is a prey generalist or specialist	Prey generalist	Prey specialist

Sensitivity attribute	Goal	Low score means	High score means
Sensitivity to Temperature	Known temperature of occurrence or distribution as a proxy for sensitivity to temperature	Species found in wide temperature range or has a distribution across wide latitudinal range and depths	Species found in limited temperature range or has a limited distribution across latitude and depths
Adult Mobility	Determine the ability of the stock to move if their current location becomes unsuitable	Highly mobile adults	Sessile adults
Dispersal of Early Life Stages	Estimate the ability of the stock to colonise new habitats	High dispersal	Low dispersal
Exposure attribute	Goal	Low score means	High score means
Sea Surface Temperature	Assess the amount of sea temperature change that has already occurred or is projected to occur	Temperature is consistent	Temperature has or will change significantly
Variability in Sea Surface Temperature	Assess if this change is a consistent trend, episodic or otherwise variable (e.g., associated with oscillations)	Low variability	High variability
Salinity	Assess the amount of salinity change that has already occurred or is projected to occur	Salinity is consistent	Salinity has or will change significantly
Variability in Salinity	Assess if this change is a consistent trend, episodic or otherwise variable (e.g., associated with oscillations)	Low variability	High variability
Precipitation	Assess the amount of precipitation change that has already occurred or is projected to occur	Precipitation is consistent	Precipitation has or will change significantly
Variability in Precipitation	Assess if this change is a consistent trend, episodic or otherwise variable (e.g., associated with oscillations)	Low variability	High variability
Ocean Acidification	Assess the amount of pH change that has already occurred or is projected to occur	pH is consistent	pH has or will change significantly
Variability in Ocean Acidification	Assess if this change is a consistent trend, episodic, or otherwise variable	Low variability	High variability
Currents	Determine if there have been or will be changes to currents in the region of interest.	Currents are consistent	Currents have or will change significantly
Sea Level Rise	Assess the amount of sea level rise that has already occurred or is projected to occur	Sea level is consistent	Sea level has or will change significantly

Table 6: Data quality scoring guidelines for the Rapid Vulnerability Assessment based on Morrison et al. (2015).

Data Quality Score:	Description
0=No data	No information to base an attribute score on. Very little is known about the species or related species or related species and there is no basis for forming an expert opinion.
1= Expert Judgement	The attribute score reflects the expert judgement of the reviewer and is based on their general knowledge of the species, or other related species, and their relative role in the ecosystem.
2= Limited Data	The score is based on data which has a higher degree of uncertainty. The data used to score the attribute may be based on related or similar species, come from outside the study area, or the reliability of the source maybe limited.
3=Adequate Data	The score is based on data which have been observed, modelled, or empirically measured for the species in question and comes from a reputable source.

Pāua (Abalone)
Climate Change Vulnerability, Adaptation Strategies, and Identified Management Options for New Zealand Waters

Fisheries New Zealand
Tini a Tangaroa

SPECIES DESCRIPTION

Pāua (*Haliotis iris, H. australis*) are endemic New Zealand abalone, occupying a narrow coastal ribbon of intertidal rocky shorelines and nearshore reefs to depths of ~15 m. They are long-lived, annual broadcast spawners (1-3 week larval stage) and feed primarily on drift algae as adults. Temperature and related factors (food) are the primary drivers of adult size. Pāua have been virtually unchanged for 65 million years, making them one of the least evolved abalone species. Pāua support important commercial (export value ~NZ$55M), customary, and recreational fisheries.

VULNERABILITY TO CLIMATE CHANGE

Pāua growth and development are influenced by water temperature, wave exposure, and food availability. Pāua are vulnerable to smothering during sedimentation events. Pāua are also affected by decreasing pH both directly and indirectly (e.g., declines in coralline algae as a food source and settlement cue), and changes in suitable substrate availability due to coastal sedimentation. Terrestrial land use changes and management practices can exacerbate climate impacts due to increases in sedimentation and reduced water quality.

Fishery implications:

- Increasing temperatures and diminishing food may reduce the number of individuals that are of harvestable size
- Altered availability of food and suitable settlement substrate may reduce stock numbers (particularly in combination with elevated sediment inputs) and animal condition
- Sedimentation reduces recruitment surface availability, increases larval mortality

OVERVIEW OF PĀUA VULNERABILITY

low — moderate — high — very high

Shellfish are vulnerable to climate change and ocean acidification, and their sessile nature makes them susceptible to rapidly changing and/or highly variable environmental conditions.

Drivers of Pāua Vulnerability

- ***Climatic and climate-associated factors and disturbance regimes:*** Enhanced coastal erosion & elevated sediment inputs, increasing sea surface temperature, ocean acidification
- ***Non-climate factors:*** Management and flood control that increase nearshore sediment delivery, illegal take, nutrient pollution, conflicting management

SUMMARY OF VULNERABILITY

PROJECTED FUTURE CHANGES *(EXPOSURE)*	POTENTIAL EFFECTS ON PĀUA *(SENSITIVITY)*	FACTORS THAT INFLUENCE ABILITY TO RESPOND TO CHANGE *(ADAPTIVE CAPACITY)*
Increasing **ocean temperature** • *+0.55-3.3°C by 2100, depending on emissions scenario* • *Largest increases likely in the Tasman Sea and south of Chatham Rise* • *Increasing marine heatwaves*	• Increased rate of larval development **NZ** • Reduced size at maturity and maximum adult size **NZ** • Altered distribution and survival of macroalgal food source **NZ** • Mortality events (Global data)	**Ecological factors that enhance adaptive capacity:** • Wide distribution around mainland New Zealand and offshore islands • Broad diet, long-lived (20-30 years) • High levels of genetic variation may provide opportunities for adaptation • Association with kelp beds may alleviate local acidification effects • Ability to raise larvae in hatcheries increases management potential (i.e., can avoid adverse conditions, selection of resilient strains)
Ocean acidification • *Oceanic pH declines of 0.13-0.33 units by 2100, depending on emissions scenario* • *Lowest pH levels will occur in the south*	• Reduced juvenile growth rates **NZ** • Greater prevalence of abnormalities in larvae **NZ** • Enhanced shell surface dissolution in juveniles **NZ** • Reduced suitable recruitment habitat and/or food availability for juveniles due to pH-related declines in coralline algae ?	**Societal factors that enhance adaptive capacity:** • High economic, societal, and cultural value (taonga species) increase support for management • Fishery employs free diving for harvest
Increasing frequency and severity of **storms** and **extreme precipitation events** • *Contributes to sudden decreases in salinity and increased sedimentation* • *Rubble abrasion of populations*	• Disrupted harvest pressure as storm events increase • Mortality from large or sudden decreases in salinity • Mortality from habitat storm disturbance *** Also see sedimentation impacts*	**Factors that reduce adaptive capacity:** • Adults are essentially sessile, increasing vulnerability to changing conditions • Extremely localised recruitment (failures reported when adult aggregation falls below 1.5 m to nearest neighbour) • Shallow habitat is more vulnerable to stressors
Increasing **coastal sedimentation** • *Deposits layers of sediment and/or elevates suspended sediment concentrations*	• Increased larval mortality due to elevated suspended sediment levels **NZ** • Settled sediments reduce availability of suitable larval settlement habitat, limiting recruitment and abundance **NZ** • Macroalgal food sources damaged by reduced light and smothering **NZ**	Data Source Symbol Key Global data **NZ** Regional data ? More information needed

Figure 10a: Page 1 of Species Summary for Pāua.

POTENTIAL ADAPTATION STRATEGIES FOR PĀUA

Note: Strategies evaluated for E (effectiveness) and F (feasibility)

Projected Change	Vulnerability of Fishery	Potential Adaptation Strategy & Management Options
Increasing **ocean temperature**	Reduced adult size resulting in fewer individuals that reach harvestable size each year	• Incorporate consideration of projected environmental change into plans for industry and NZ fisheries management *(High E/High F)* • Adjust catch size (where maturing smaller, recalculate sustainable harvest, if population has reset to smaller size) *(High E/Mod F)* • Change collection and harvest regulations *(High E/Mod F)* • Enhance pāua resilience to increasing ocean temperatures by reducing other stressors that are detrimental to growth (e.g., water quality) via effective catchment management *(High E/Low F)* • Continue investigation of pāua ability to acclimate or adapt to rising temperatures (growth, time to and length at maturity, mortality rates, variability by region), and incorporate knowledge into management plans *(High E/Mod F)* • Use traditional aquaculture, although cooling costs may limit economic feasibility *(High E/Mod F)* • Translocate individuals from slow-growing/depleted sites to fast-growing sites to achieve greater biomass *(High E/High F)*

	Reduced survival, especially when combined with other stressors	• Manage sediment input and other stressors where necessary *(High E/Low F)*
		  • *Create fisheries plans (Section IIA plans) for inclusion in regional plans*
		  • *Address land use and flood management*
		  • *Enforce the Resource Management Act across the whole catchment*
		• Seasonal closures of fishery or sites (determine most effective timing for closures) *(Low E/High F)*

	Reduced survival of algal food source	• Habitat enhancement to support algae *(Low E/Low F)* • Manage environment health to sustain preferred algae (reduce other stressors that are detrimental to survival) *(Mod E/Low F)*
	Potential impacts on spawning and larvae	• Increase understanding of vulnerability to marine heat waves/extreme events through existing research and translation to scale *(Mod E/Mod F)* • Research and select broodstock that is naturally more resilient to changes in temperature, pH, and disease, and incorporate these into breeding programmes *(Mod E/Mod F)*
Ocean acidification (OA)	Shells eroded, settlement habitat may be diminished	• Continue to investigate the ability of pāua to acclimate or adapt to ocean acidification *(High E/Mod F)* • Test management actions to increase OA resilience (e.g., return crushed shells to sites unknown *E/Mod F*, identify resilient families *High E/High F*) • Ocean ranching (movement to suitable habitat at each lifestage) *(High E/High F)*
	Fewer individuals that reach harvestable size each year	• Incorporate consideration of projected environmental change into plans for industry and NZ fisheries *(High E/High F)* • Change collection and harvest regulations *(High E/Mod F)* • Identify/map suitable locations for juvenile planting and managed area designation *(Mod E/Mod F)* • Hatchery-based farming, managed brood stock, spawning, and rearing through vulnerable life stages *(High E/Mod F)* • Ocean ranching (movement to suitable habitat at each lifestage) *(High E/High F)* • Use traditional aquaculture *(High E/Mod F)* • Marine aquaculture hybrid (build facility out of buffering substrate) *(Unknown E/Unknown F)*
Enhanced **coastal sedimentation** and **erosion**	Reduced availability of suitable substrate, limiting recruitment and abundance	• Develop best management practices for different land uses to reduce nearshore sedimentation *(High E/Mod F)*
Decreased O_2	Range shifts, decreased growth rates, decreased survival	• Global issue of potential importance to New Zealand. Research specific to pāua needed *(unknown E/High F)* • Identify and protect higher O_2 refugia (places of disturbance) *(unknown E/unknown F)*

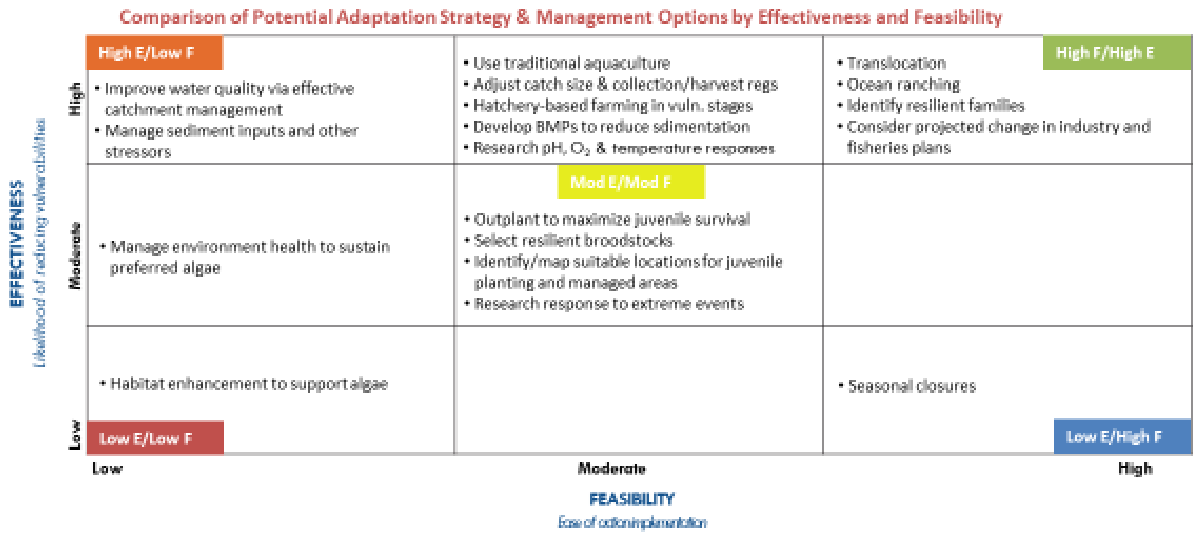


Figure 10b: Page 2 of Species Summary for Pāua.

Hoki

Climate Change Vulnerability, Adaptation Strategies, and Potential Management Options for New Zealand Waters

Fisheries New Zealand
Tini a Tangaroa

SPECIES DESCRIPTION

Hoki (*Macruronus novaezelandiae*) is a bentho-pelagic species found primarily offshore along New Zealand's continental shelf, particularly south of 41°S, to depths of 1200 m with adults (ages four and older) occupying deeper water (>400 m). Hoki spawn from late June to mid-September. Larvae inhabit shallower/inshore areas, while juveniles are widespread at age one year, concentrating on the Chatham Rise by age two years. Hoki adults feed primarily on euphausiids, mesopelagic fishes, natant decapods, and squid. Hoki support New Zealand's most valuable deepwater fishery (NZ $229 M in 2017).

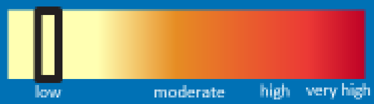
VULNERABILITY TO CLIMATE CHANGE

Hoki recruitment, and associated year-class strength, is likely influenced by change and ocean conditions (e.g., water temperature, changes in the Southern Oscillation Index, wind patterns). However, the form and strength of these relationships is unclear. Hoki may also be indirectly affected by pH-driven declines in main prey sources (e.g., euphausiids, decapods) and impacts to primary production. Additionally, conditions in areas that support adults may not be appropriate for reproduction and larval survival. Changes in hoki population structure as a result of climate changes may be further exacerbated by fishing pressure.

Fishery implications:

- Variable (and potentially altered) recruitment will affect fishery stock size/productivity
- Altered food availability may affect fish growth and reproduction
- Altered distribution may affect fishing success
- Larval survival may be reduced due to ocean acidification

OVERVIEW OF HOKI VULNERABILITY



Offshore fish such as the hoki experience a variety of interacting factors (e.g., temperature, circulation, stratification), making it difficult to draw direct linkages between environmental variables and stock performance.

Drivers of Hoki Vulnerability

- ***Climatic factors and disturbance regimes:*** Increasing ocean temperature, oceanic winds, upwelling, ocean acidification
- ***Non-climate factors:*** Fishing

SUMMARY OF VULNERABILITY

PROJECTED FUTURE CHANGES *(EXPOSURE)*	POTENTIAL EFFECTS ON HOKI *(SENSITIVITY)*	FACTORS THAT INFLUENCE ABILITY TO RESPOND TO CHANGE *(ADAPTIVE CAPACITY)*
Increasing **ocean temperature** • *+0.55-3.3°C by 2100, depending on emissions scenario* • *Increases in mid- to deep ocean water temperature also likely*	• Enhanced biomass variability, with declines in recruitment and biomass likely ? • Potential shifts in distribution; currently found in areas 6-12°C (mean=9°C) ?	**Factors that enhance adaptive capacity:** • Widely distributed and highly mobile *NZ* • Relatively long-lived (20-25 yrs) *NZ* • Multiple egg batches produced per year *NZ* • Two sub-populations; unknown if sub-populations are genetically distinct ? • High economic value may increase support for management *NZ* • Broad range of pH tolerance in adults *NZ*
Shifts in **oceanic winds** and the **Australian current**	• Altered food availability, influencing growth & survival *NZ* • Decreased growth and fitness • Influence recruitment variability *NZ*	
Ocean acidification • *pH declines of 0.13-0.33 units by 2100, depending on emissions scenario* • *pH levels lower at locations farther south*	• May reduce availability of sensitive prey species (e.g., euphausiids, decapods) • Metabolic changes may affect behaviour and larval survival ? • Reduced larval survival	**Factors that undermine adaptive capacity:** *NZ* • Not all adults reproduce annually **Data Source Symbol Key** Global data *NZ* Regional data ? More information needed

Figure 11a: Page 1 of Species Summary for Hoki.

POTENTIAL ADAPTATION STRATEGIES FOR HOKI

Note: Strategies evaluated for E (effectiveness) and F (feasibility)

Projected Change	Vulnerability to Fishery	Potential Adaptation Strategy & Management Options*
Increasing **ocean temperature**	Reductions and variability in available biomass	• Reduce fishing pressure in cold-water areas *(Mod E/Mod F)* • Update stock assessments to include projected temperature *(Mod E/High F)* • Gather data to adjust target threshold of total allowable catch*(High E/High F)* • Limit catch size to protect sensitive size classes *(Mod E/Mod F)*
	Changes/variability in recruitment	• Increase knowledge (e.g., reestablish annual surveys, monitor in new areas, observation by year class) *(Mod-High E/High F)* • Update stock assessment to account for changes *(Mod E/High F)* • Promote precautionary management (e.g., run projection scenarios with lower recruitment) *(Mod E/High F)* • Enhance fisheries (e.g., hatcheries) *(Low E/Low F)*
	Spawning declines	• Identify new spawning locations *(Low E/Low F)* • Close spawning locations to fishing during spawning period (e.g., seasonal area closures) *(Mod E/Low F)* • Change quota effort areas *(Mod E/Low F)* • Minimise effect on existing spawning sites*(Mod E/Low F)* • Increase spawning site survey frequency and extend survey area *(Mod E/High F)*
	Reduced ability to catch fish	• Update stock assessment to account for changes in catch, include environmental variability, altered recruitment levels, population size associated with decreased growth rate, resource limitation resulting in intraspecific competition *(Mod E/High F)*
	Range shifts (distribution to new areas ~9°C)	• Identify and protect temperature refugia *(Mod E/Low-Mod F)* • Identify and manage populations expanding into new areas *(Mod E/Mod F)*
Shifts in **oceanic winds** and **currents**	Reduction in size and availability	• Change in harvest regulations to reflect new rates of growth and population density *(High E/High F)*
	Changes in distribution due to movement and growth of young	• Monitor and manage populations expanding into new areas *(Mod E/Mod F)* • Investigate distribution changes *(Mod E/Mod F)* • Increase target level for fisheries *(Mod E/Mod F)* • Do nothing (expansion into mid-column is unfishable) *(Low E/High F)*
Ocean acidification (OA)	•Prey availability reduction relocates populations •Metabolic and behavioural changes reduce growth and survival	• Actively manage expanding populations where range expansion occurs in order to reduce the impacts of ocean acidification *(Mod E/Mod F)* • Investigate direct (i.e. behavioural) and indirect (e.g., altered prey availability) ocean acidification impacts on hoki *(Mod E/Low F)*

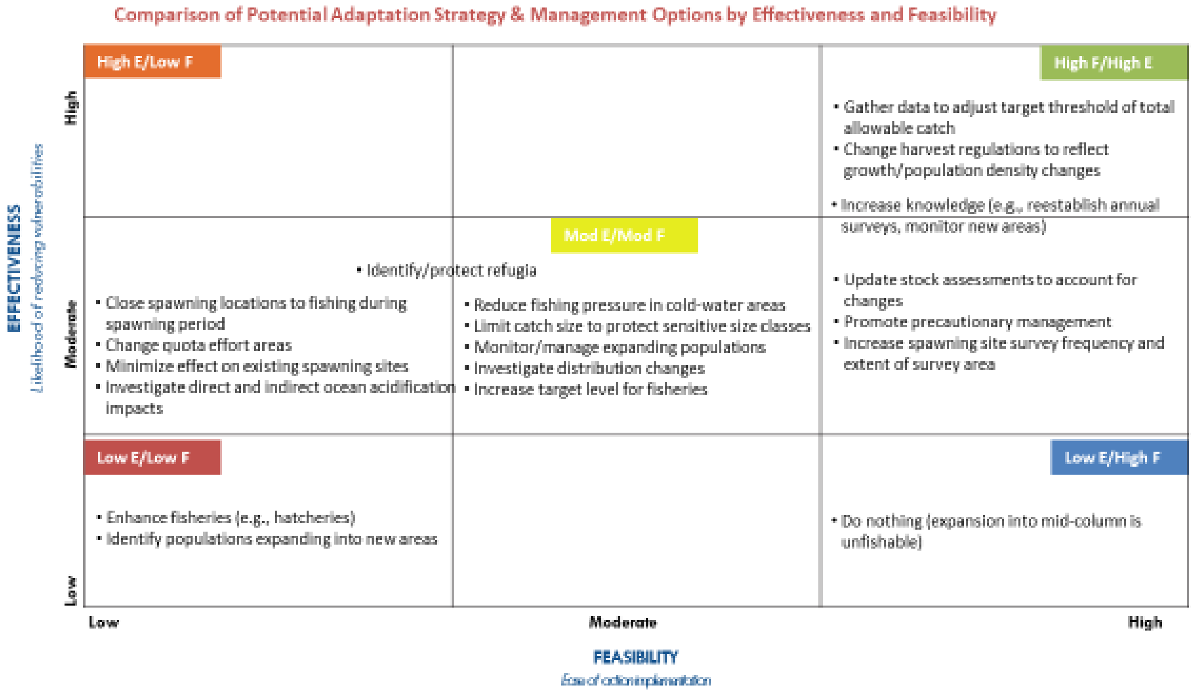


Figure 11b: Page 2 of Species Summary for Hoki.

Snapper

Climate Change Vulnerability, Adaptation Strategies, and Potential Management Options for New Zealand Waters

Fisheries New Zealand
Tini a Tangaroa

SPECIES DESCRIPTION

Snapper (*Chrysophrys auratus*) is an inshore demersal fish found in shallow water (shoreline to 250 m, abundant to 100 m), occupying many different inshore habitats (e.g., rocky and biogenic reefs, mud and sand bottom areas). Shallow estuaries, bays, and harbours are very important for juveniles. Snapper spawn from September to March, aggregating between 20 and 30m. Snapper larvae are pelagic. As young juveniles, they feed predominantly on pelagic items (copepods) before switching to a largely benthic diet. Snapper support valuable commercial (NZ$33 M export value in 2017) and recreational fisheries, as well as important customary fisheries.

VULNERABILITY TO CLIMATE CHANGE

Snapper are primarily sensitive to water temperature increases, which may expand spawning opportunities, increase recruitment, and drive southerly range expansions, but effects are uncertain. However, ocean acidification may also affect swimming behaviour and alter prey availability. Snapper recruitment will also be influenced by changes in estuarine conditions, primarily turbidity, sedimentation, and food web dynamics. Land use activities that increase sedimentation and turbidity and/or degrade water quality (e.g., by increasing nutrient runoff) in estuarine habitats may reduce larval and juvenile recruitment.

Fishery implications:

- Altered stock size (increases likely if estuaries are healthy)
- Expanded distribution may create new fishing opportunities

OVERVIEW OF SNAPPER VULNERABILITY

Inshore fish may experience higher vulnerability due to use of near-shore habitats, where non-climate stressors can exacerbate climate-driven changes in water quality.

Drivers of Snapper Vulnerability

- ***Climatic factors and disturbance regimes:*** Increasing ocean temperature, decreased dissolved oxygen, ocean acidification, coastal erosion & sedimentation, altered precipitation, increased storm frequency and severity
- ***Non-climate factors:*** Land-based activities that reduce water quality (sedimentation, pollutants such as heavy metals, fertilizers)

SUMMARY OF VULNERABILITY

PROJECTED FUTURE CHANGES *(EXPOSURE)*	POTENTIAL EFFECTS ON SNAPPER *(SENSITIVITY)*	FACTORS THAT INFLUENCE ABILITY TO RESPOND TO CHANGE *(ADAPTIVE CAPACITY)*
Increasing **ocean temperature** • *+0.55-3.3°C by 2100, depending on emissions scenario* • *Largest increases likely to occur in the Tasman Sea & Sub-Antarctic south of Chatham Rise*	• More parasites, disease, and predatory species • Increased frequency of harmful algae blooms • Earlier spring spawning (onset at 14.8-16°C) NZ • Accelerated larval development and growth with warming, or negative impacts if temperatures exceed thermal maxima NZ • Increased recruitment; highest recruitment occurs during years with warmest autumn sea surface temperatures (20°C), may vary by stock NZ • Potential shifts in distribution (e.g., expansion south) due to wide temperature tolerance ? • Possible impacts on adult growth and mortality (similar to Atlantic cod)	**Ecological factors that enhance adaptive capacity:** • Abundant within current range NZ • Adults are habitat and prey generalists • Wide temperature range that may allow opportunity for expansion NZ • Long-lived (60+ yrs) • Serial spawners (release several egg batches each spawning season) NZ • Six to seven biological stocks (although limited mixing between stocks) NZ **Societal factors that enhance adaptive capacity:** • High economic and social value may increase support for management
Decreased **dissolved oxygen**	• Increased juvenile mortality • Decreased growth and fitness	**Factors that undermine adaptive capacity:** • Juvenile use of bays and estuaries exposes them to increased sedimentation, pollution, and decreased oxygen levels from terrestrial land use • Larvae and post settlement juveniles exhibit fewer generalist tendencies compared to adults
Ocean acidification • *pH declines of 0.13-0.33 units by 2100, depending on emissions scenario* • *pH levels lower at locations farther south*	• Could alter prey availability, particularly for larval snapper (algae and copepods) • Metabolic changes may affect behavior, physiology and survival to adulthood, with both positive and negative effects possible	
Increased **coastal sedimentation** (e.g., due to increasing **storm frequency and severity**) or altered **precipitation**	• Increased turbidity can reduce foraging success NZ • Increased sedimentation in nursery estuaries could reduce recruitment (e.g., via shading of seagrass habitat) • More westerlies reduce wave impacts on seabed NZ	Data Source Symbol Key Global data NZ Regional data ? More information needed
Sea level rise	• Juvenile habitat loss or expansion	

Figure 12a: Page 1 of Species Summary for Snapper.

POTENTIAL ADAPTATION STRATEGIES FOR SNAPPER

Note: Strategies evaluated for E (effectiveness) and F (feasibility)

Projected Change	Vulnerability to Fishery	Potential Adaptation Strategy & Management Options
Increasing **sea surface temperature**	Range expansion to the south	• Protect potential estuarine nursery habitat in new range areas in order to facilitate range expansion • Change total allowable commercial catch for SNA 3 quota holders *(Low E/High F)* • Stock boundary changes (by Minister: for sustainability or by 75% of quota owners) *(High E/Low-Mod F)* • Subdivide Quota Management Areas for more accurate assessment and monitoring *(Mod E/Mod F)* • Expand monitoring where stock numbers increase (e.g., trawl survey, catch/effort report) *(Low-Mod E/High F)* • Encourage sedimentation abatement strategies in southern juvenile sites *(High E/Low-Mod F)*
	Shifts in distribution of parasites, disease, predators and competitors	• Update stock assessment (e.g., age structure, growth rate) to include climate change factors *(Mod E/High F)* • Identify differences in stock responses to climate change by population and age *(Mod E/High F)* • Measure size at maturity to determine whether it changes by location in range *(Mod E/High F)* • Monitor transitions (e.g., new species and pathologies) to inform fishery and management *(Mod E/High F)*
	Toxicity and decreased dissolved oxygen due to harmful algae blooms	• Expand efforts to decrease sediment and pollution in nearshore coastal waters (see actions related to water quality below) *(High E/Low F)*
Decreasing **dissolved oxygen**	Range contraction from the south due to due to decreased oxygen in warmer water temperatures; decreased productivity and abundance	• Stock assessment modifications – recruitment sensitivity, growth rates with different food *(High E/High F)* •Decrease total allowable commercial catch as stock size decreases (5 year time horizons) •Management strategy evaluation with climate parameters changes (e.g., monitoring age structure, simulations with climate parameters and related impacts) •Change quota according to stock assessment *(High E/Low F)* •Decrease quota to compensate for population declines *(Mod E/High F)*
Ocean acidification	Population declines due to acidification (direct & indirect)	• Reduce land-based pollution that contributes to declining ocean pH *(High E/Low F)*
Coastal erosion and sedimentation	Reduced recruitment and foraging success affect population numbers	• Reduce human contributions to erosion and sedimentation through changes in land management and flood control *(High E/Low F)*
	Loss of habitat and prey for juveniles	• Expand efforts to improve water quality in estuaries, bays and harbours *(High E/High F)* •Fencing paddocks to keep livestock and run-off away from watershed elements •Riparian plantings to reduce water temperature and increase filtration •Sedimentation ponds for milking and other effluent • Regional Council work on engineering waterways includes planning for climate change impacts • Forestry management should include managed wetlands • Wetland reengineering/replacement *(Mod E/Low-Mod F)*
Shoreline hardening and coastal development	Possible expansion or contraction of juvenile habitat, although new habitat may be degraded due to pollution and/or sedimentation	• Improved coastal mapping, including sea level rise, flooding, across all scales of coastal risk *(Mod E/High F)*

*Actions presented are those ranked as having higher feasibility and/or effectiveness.

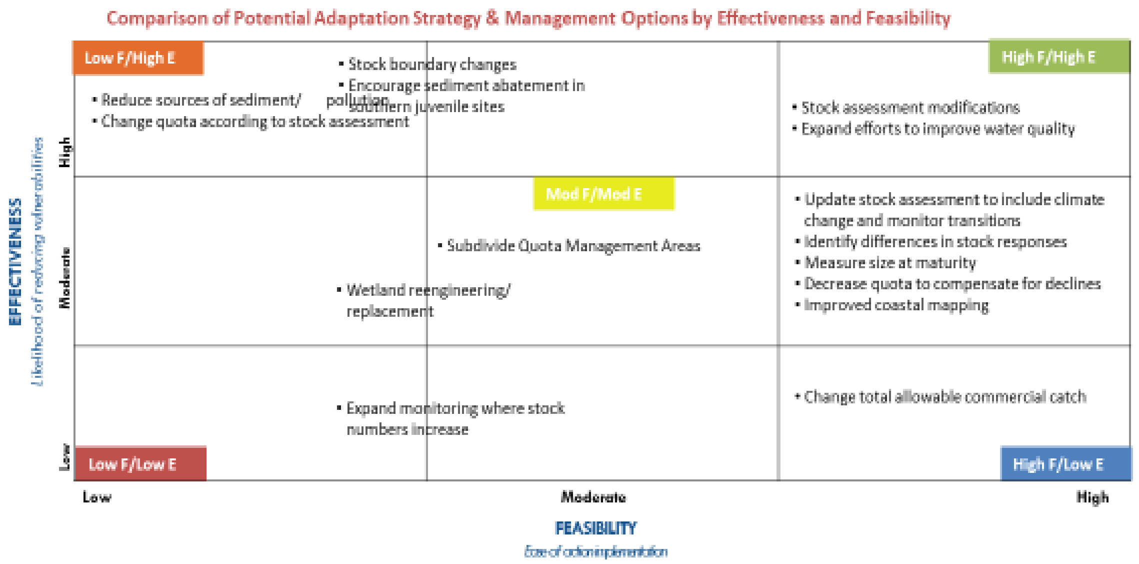


Figure 12b: Page 2 of Species Summary for Snapper.

6. CONCLUSIONS

Predicting the effects of climate variations on fisheries and aquaculture is currently limited by the understanding of how large-scale climate patterns affect the oceanography of New Zealand waters, how environmental variability affects species, and how species interact in an ecosystem (Hurst et al. 2012; MPI 2014). The shortness of time series of observations makes it difficult to determine how much change in New Zealand's marine ecosystems to date is due to anthropogenic climate change rather than due to natural climate cycles and variability, or other factors, and what ecosystem changes are likely in the future (Francis & Hare 1994; Bradford-Grieve & Livingston 2011; Hurst et al. 2012; Pinkerton et al. 2019). This report provides details of both the state of knowledge of climate change parameters in the marine environment, how these parameters are likely to influence the suite of selected fish species and stocks, and what uncertainties remain in our understanding of climate change implications for New Zealand fisheries. A supporting Synthesis document (Specific Objective 2) will present technical information in a format more easily transferable into fisheries management and policy both for managers and for the fisheries community.

This report has reviewed the *state of knowledge* of climate change associated predictions for components of New Zealand's marine environment that are most relevant to fisheries (Chapter 2). It also reviewed biological and ecological characteristics of 32 key fisheries species (Chapter 3) and, based on this knowledge, evaluated whether these species might be affected by changes expected to selected properties of New Zealand's oceanic and coastal waters over the remainder of this century (Chapter 4).

It is clear from Chapter 2 that a complete understanding of the response of key New Zealand fisheries species to climate-associated change, based on scientific data, is difficult given the lack of information both on the species and the potential threats they face (e.g., see the many cells containing question marks in Table 3). Nevertheless, 13 of the 21 species groups evaluated to date may be affected by warming, and seven by ocean acidification (Table 3) supporting the finding of MacDiarmid et al. (2012) that these are the two greatest anthropogenic CO_2 associated threats facing our marine environment.

This technical report (Specific Objective 1) and its synthesis document (Specific Objective 2) provide this comprehensive summary of current state of knowledge on the impacts of climate change on the New Zealand fisheries sector. Three individual species summaries, for pāua (shellfish), snapper (inshore), and hoki (middle depths/deepwater) were co-developed with fisheries scientists, managers, and industry members with substantial knowledge of the current state and likely responses of each fishery to climate drivers (Chapter 5).

To further increase the benefit of the synthesis document and the species-specific evaluation tools (assessed for pāua, snapper, and hoki, Chapter 5) for the potential user community, an online interface in the Climate Adaptation Knowledge Exchange (http://www.cakex.org/) will also be available to further improve access and dissemination of the summary report content and supporting materials.

6.1 Gaps and next steps

Although this project has summarised key gaps in the understanding of how fisheries may respond to climate change, many new developments at both the fisheries science and policy levels are recognising and responding to these gaps. These responses include new science projects targeting climate-related uncertainties for the fisheries sector, and governmental and external reviews noting key priorities to fill information gaps in the response to climate change. Altogether these actions are promising and show evidence of a clear recognition of the need to better understand climate change impacts, both in science funding and policy reviews. The risk assessment framework used to detail climate change responses for three fisheries was particularly successful at highlighting the usefulness of risk assessment approaches for individual species and sectors to highlight knowledge gaps for individual species and sectors.

New science projects have been initiated to fill climate change-fisheries knowledge gaps. In particular, three MPI (now Fisheries New Zealand) projects have been initiated: 1) "Climate change, fish distribution meta-analysis" (ZBD2018-02); 2) "Climate variability, trends and fish population parameters" (ZBD2018-03); and 3) "Ecosystem function and regime shifts in the Sub-Antarctic" (ZBD2018-05). The first of these (ZBD2018-02) is investigating changes in species distribution and stock productivity that are potentially attributable to climate-related changes in environmental variables. Understanding these shifts in species distributional patterns in relation to fisheries management area boundaries and stock productivity is key to adaptation and management under a changing environment. A second project (ZBD2018-03) is examining how different stock assessment parameters (e.g., recruitment and productivity parameters such as natural mortality, steepness, von Bertalanffy growth curves, length-weight relationships, recruitment variability, and the mean number of recruits) vary over time, and how these parameters might change due to climate-related impacts on the ocean. The project will identify suitable indicator parameters for monitoring change in 20 fisheries including finfish, rock lobster, and pāua. The third project (ZBD2018-05) will use a whole of system modelling approach based on information from numerous data sources to explore environmental shifts in the Subantarctic over the past 40 years, and how these shifts may be influencing different biota, including megafauna, top predators, protected species, and fish. Ecosystem models will explore the effects of environmental variability and change at the scale of decades affecting ecosystem function in the Subantarctic, including effects on protected species (e.g., New Zealand sea lions, Antipodean albatross, yellow-eyed penguins, other seabirds) and on ecologically and economically important fish (e.g., hoki, squid, southern blue whiting).

Numerous governmental and external reviews have highlighted climate change and its importance for New Zealand's ocean ecosystems and sustainable fisheries. These policy reviews provide evidence of the broad scale recognition of the potential effects of climate change, and the need for adaptive management to fill key gaps in understanding. For example, the Te Mana o te Taiao – Aotearoa New Zealand Biodiversity Strategy (ANZBS) 2020 (Department of Conservation 2020) specifically refers to climate change in its section 3.2.2, where it highlights sea level rise, ocean acidification, and increased sea temperature as the largest threats that are likely to compromise the extent and health of coastal and marine ecosystems and species. Climate is also pervasive within the ANZBS Theory of Change Framework. The Parliamentary Commission for the Environment's 2019 Environment Reporting (Parliamentary Commission for the Environment 2019) is organised around 5 themes, one of which is climate change. With particular reference to fisheries, the report notes that "*Marine biodiversity is poorly understood, and we have only a limited understanding of the impact our various activities are having on our marine ecosystems. Current fisheries management systems have a single-species focus and rarely take into account the effects of fishing on the wider ecosystem. For example, ecosystem changes due to fishing and climate change are rarely explicitly included in the single-species fisheries management carried out in New Zealand*."

Finally, the New Zealand Environmental Reporting Series on 'Our Marine Environment 2019' (Ministry for the Environment & Stats NZ 2019) highlights climate change as one of four key issues affecting marine ecosystems, including taonga species. The report highlights, in particular, the uncertainty about the impacts of climate change on primary productivity in the oceans, and how ocean warming is expected to strengthen vertical stratification, resulting in reduction in the supply of nutrients in some regions of New Zealand. The report highlights the flow-on effects on primary productivity for the whole food web, as well as changes in species distribution and reductions in some habitats (e.g., kelp forest) with warming waters and marine heatwave events. This report specifically refers to the fisheries sector, suggesting that *"Past approaches to fisheries management and catch levels may no longer work for some species and stocks",* citing influences of temperature changes on fish distributions. Vulnerability to aquaculture was highlighted including heatwave impacts resulting in mortality events, and associated loss of revenue, and vulnerability to ocean acidification of many taonga species including pāua, cockles, kuku (green-lipped mussel), and kina (sea urchin).

Novel explorations of the future of fisheries include a new (2020) report on climate-related scenarios for aquaculture and fisheries, sponsored by The Aotearoa Circle (The Aotearoa Circle 2020). This report was intended to challenge assumptions about the future of New Zealand's fisheries and aquaculture sectors and stimulate critical thinking and timely response. Key insights for fisheries, under a rapid warming 'Māko' scenario or a strong mitigation 'Kahawai' scenario are: 1) the need for fisheries to consider consumer demand for safe, secure, and sustainable protein; 2) that flexible, responsive policy and regulation will be critical to the sector's future success in maximising this comparative advantage; and 3) that climate impacts in the fisheries sector are likely to be swift and profound, requiring strategic and adaptive management to avoid risks and maximise opportunities.

Some initiatives with respect to sustainable fisheries have only recently commenced. Following the Fisheries Management System review (in 2015), a major new work programme was developed, entitled the Fisheries Change Programme (https://www.mpi.govt.nz/protection-and-response/sustainable-fisheries/strengthening-fisheries-management/fisheries-change-programme/) with objectives to a) "strengthen and modernise the way we manage our fisheries", and b) "ensure the sustainability of New Zealand's fisheries". A National Environmental Standard (NES-MA) has been developed for marine aquaculture, which will provide a nationally consistent approach for resource consent processes for aquaculture, including the expanding interest in offshore finfish aquaculture (New Zealand Government 2020). This new standard came into force in December 2020 (https://www.mpi.govt.nz/growing-and-harvesting/aquaculture/national-environmental-standards-for-marine-aquaculture/); it includes guidance to support the industry to adapt to climate change. An additional follow-on initiative is the "Keeping Aotearoa New Zealand at the leading edge of global fisheries management", an expert panel review which seeks to identify innovative technologies and methods that can be applied to fisheries to achieve goals of an integrated approach to fisheries management, which includes consideration of the wider environment and its inhabitants. This expert panel is being convened by the Office of the Prime Minister's Science Advisor.

6.2 Final comments

This project has benefitted from awareness of aligned research within the Fisheries New Zealand Fisheries portfolio (e.g., recently initiated project on climate change drivers of fishery stock assessment parameters), other central and regional government funding (e.g., Ministry for the Environment funding on climate indicators), and MBIE research portfolio (e.g., CARIM project on ocean acidification).

Ongoing communication with Fisheries New Zealand advisors to the project led to iterative discussions of the species chosen, the workshop format and timing, and the content of the progress reports (Cummings et al. 2016a, 2017, 2018). Throughout the project's life (2014–2019), the list of species and stocks of interest was modified and expanded to ensure those of particular interest to Fisheries New Zealand and the fishing industry were included in the assessment. Proposed workshop logistics were modified, and their timing adjusted, with choice of species for trials of different tools chosen directly from input by Fisheries New Zealand. For example, at the request of Fisheries New Zealand, a summary table (Table 4) was compiled to focus on the implications of environmental change to the fisheries species from a stock assessment parameter perspective, rather than the original focus on climate change drivers (Table 3; see also Cummings et al. 2018). This change allowed for better linking of potential interactions of climate change on fisheries with the stock assessment parameters (e.g., survival, recruitment) that are most likely to be affected, allowing for discussion of management actions to reflect uncertainty within stock assessments, rather than the prior emphasis on climate change drivers (for which mitigation is not under the realm of Fisheries New Zealand management).

From the analyses presented here, it is clear that the relatively poor state of knowledge of potential impacts of environmental change on New Zealand fish species means that risk assessments will be very difficult for most species.

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APPENDIX 1: Key New Zealand fisheries species – state of knowledge summaries

The text below summarises the state of knowledge of the 32 selected species groups relating to aspects that may be impacted by climate change (e.g., their geographical distribution, preferred depth and water temperature ranges, main dietary components). Clearly, all these species could be impacted by any environmental change that alters water temperatures, water chemistry, or the behaviour of currents. Effects could be direct (e.g., result from a change that effects survival or functioning of the organism) or indirect (e.g., in response to climate change induced alteration of the abundance or availability of preferred prey). Where they are apparent, these challenges are noted by species.

Species summaries are listed alphabetically, based on their common name, below.

STATE OF KNOWLEDGE SUMMARY

Albacore (ALB), *Thunnus alalunga*, Ahipataha

Characteristic	Details	Reference
Fishery	Albacore tuna, also known as longfin tuna, are a summer troll fishery (the majority of the catch), as well as a year round longline fishery and some pole & line and hand line fishing. An important recreational species. Most likely part of the catch of early Māori. Commercial fishing of albacore in New Zealand waters began in 1972 around the North Island (Bay of Plenty to Napier and New Plymouth). The first commercial catches off Greymouth and Westport (54% of the total catch) were in 1973. Tuna longlining was not established as a fishing method in the domestic industry until the early 1990s.	MPI 2016c; Harley et al. 2015
Habitat	A highly migratory schooling species found in the epipelagic and mesopelagic zones.	FishBase
Distribution	An epipelagic and mesopelagic, oceanic species found in the open waters of all tropical and temperate oceans. The main distribution in New Zealand waters, is based on the fish distribution. Fishing (including recreational) occurs primarily on the west coasts of the North and South Islands. Recreational fishers target albacore off the east coast of the North Island from the Bay of Plenty to Wairarapa, and the northern east coast of the South Island. Early catch data indicate an east coast North Island distribution - Auckland to Napier.	MPI 2016c; FishBase
Stock structure	Two stocks (North and South Pacific) recognised. The South Pacific stock is distributed from the coast of Australia and archipelagic waters of Papua New Guinea eastward to the coast of South America south of the equator to at least 49° S. However, there is some suggestion of gene flow between the North and South Pacific stocks based on an analysis of genetic population structure.	MPI 2016c
Depth range	Surface waters down to 600 m.	FishBase
Temperature range	Globally abundant in surface waters of 15.6 °C to 19.4 °C; deeper swimming, large albacore are found in waters of 13.5 °C to 25.2 °C; temperatures as low as 9.5°C may be tolerated for short periods. In New Zealand waters, albacore tuna are usually found at temperatures above 18 °C. Known to concentrate along thermal discontinuities. Albacore favour those areas where cooler water interfaces with warmer water.	FishBase
Recruitment	Recruitment is estimated from a time series of modal progressions in the available catch length frequency data. There is no indication that current levels of catch are impacting recruitment.	MPI 2016c
Reproduction	Most fish found in NZ waters are juveniles and no spawning occurs here. Fifty-percent are mature by 87 cm fork length.	FishBase; Farley et al. 2012
Growth	Longevity is at least 14 years, with significant variation in growth between sexes and across longitudes. Suggested that variation in oceanography, particularly the depth of the thermocline, may affect regional productivity and therefore play a role in modifying growth.	Farley et al. 2012

Diet	Feed opportunistically on a mixture of fish, crustaceans, squid, and juveniles and also on a variety of zooplankton and micronecton species. Consumes a wide diet.	MPI 2016c
Possible climate change challenges	A southward shift in the 18 ºC isotherm will result in a southward movement of albacore. There may be a positive effect on the fishery from changes in water temperatures. The fishery has been characterised by periodic poor years that have been linked to poor weather or colder than average summer seasons. It is suggested that a variation in oceanography, particularly the depth of the thermocline, may affect regional productivity and therefore play a role in modifying growth of South Pacific albacore.	

STATE OF KNOWLEDGE SUMMARY

Arrow squid (SQU), *Nototodarus sloanii, N.gouldi*, Wheketere

Characteristic	Details	Reference
Fishery	The New Zealand arrow squid fishery is based on two related species. Fishing for squid around the Auckland and Campbell islands is exclusively by trawl. In all other areas, catch is taken by trawl and jig (although catches by the jig fishery have been at low levels since the late 1990s).	MPI 2015a
Habitat	Both species are bentho-pelagic. They range from near-shore to offshore shelf fringes.	
Distribution	Both species are found over the continental shelf in waters up to 500 m deep. *N. gouldi* is found around mainland New Zealand north of the Subtropical Front, whereas *N. sloanii* is found in and to the south of the Subtropical Front.	Anderson et al. 1998
Stock structure	Spawning areas and some spawning migrations are known but stock boundaries are not well understood; the Chatham Islands stock is probably separate, based on discontinuous distribution and age and growth characteristics.	MPI 2015a
Depth range	Found from surface waters to about 500 m, most of the commercial catch is taken between 50 and 400 m. About 95% of occurrence in the research trawl catch occurred between 70 and 440 m, with the mean depth being 200 m.	Hurst et al. 2000; Anderson et al. 1998; Figure 8
Temperature range	Found in a narrow temperature range (95% interval 8–11 °C) with a mean at 9.6 °C.	Figure 8
Recruitment	The available biomass is known to vary markedly between years, with abundance (equivalent to recruitment) well correlated with various ocean climate variables.	Hurst et al. 2012
Reproduction	*N. sloanii* spawn in June and July, and probably hatch in July and August. *N. gouldi* may spawn one to two months before *N. sloanii*, although there are indications that *N. sloanii* also spawns at other times of the year.	Uozumi 1998
Growth	Based on banding in statoliths from *N. sloanii*, these squid live for around one year. Growth is rapid. Modal analysis has shown increases of 3.0–4.5 cm per month for *N. gouldi* measuring between 10 and 34 cm mantle length.	Uozumi & Ohara 1992; MPI 2015a
Diet	Predominantly preys on mesopelagic fishes, with some crustaceans and cephalopods. The most important identified prey species was *Maurolicus australis* followed by *Lampanyctodes hectoris* and unidentified squids (Teuthoidea).	Dunn 2009
Possible climate change challenges	Appears to prefer a narrow temperature range, so changes in water temperatures could influence their distribution.	

STATE OF KNOWLEDGE SUMMARY

Barracouta (BAR), (*Thyrsites atun*), Manga, maka

Characteristic	Details	Reference
Fishery	Taken almost exclusively by trawl (both bottom and midwater). Major target fisheries have developed on spring spawning aggregations (Stewart Island, and the western, northern, and central east coasts of South Island) as well as on summer feeding aggregations, particularly around the Snares shelf and off the east coast of South Island. Also a significant bycatch in the west coast North Island jack mackerel and Snares shelf squid fisheries.	MPI 2015a
Habitat	A bentho-pelagic species. Ranges from near-shore to offshore shelf fringes.	
Distribution	Occurs on the coastal shelf around the New Zealand mainland, on the Auckland Island shelf, at the Chatham Islands, and on the shallower parts of the western Chatham Rise. Juveniles have been recorded from inshore areas (less than 100 m) all around New Zealand and at the Chatham Islands.	Anderson et al. 1998
Stock structure	Stock boundaries are not well understood, but the Chatham Islands stock is probably separate.	MPI 2015a
Depth range	Found from near-shore to about 450 m. Most of the commercial catch is from depths between 20 and 350 m. About 95% of the research trawl catch occurred between 30 and 260 m, with the mean depth being 100 m.	Hurst et al. 2000, Anderson et al. 1998, Figure 8
Temperature range	Found in a broad temperature range (95% interval 7–15 °C) with a mean at 12.0 ºC.	Figure 8
Recruitment	Recruitment variability is probably quite high for barracouta, but the drivers are unknown.	Horn 2002
Reproduction	Barracouta spawn mainly in late-winter/spring off the east and west coasts of both of the main islands, and in late spring in Southland and at the Chatham Islands. However, actively spawning fish are frequently found outside these periods. Sexual maturity is reached at about 50–60 cm fork length (FL) or about 2–3 years of age.	MPI 2017
Growth	Barracouta are relatively fast-growing and short-lived. Maximum age is about 13 years. Females grow to a larger maximum size, and may have a slightly longer life-expectancy, than males.	Horn 2002
Diet	Crustaceans (mainly euphausiids and galatheids) are the most important prey. Teleosts (mainly hoki, javelinfish and smaller species like myctophids or sprats) are the secondary prey group. Squid are also recorded frequently.	Dunn et al. 2009c; Stevens et al. 2011
Possible climate change challenges	Krill (euphausiids), a major prey species for barracouta, are potentially impacted by ocean acidification [e.g., early life stages of Antarctic krill are impacted, whereas adults are more robust (Kawaguchi et al. 2013 and Ericson et al. 2018, respectively)].	

STATE OF KNOWLEDGE SUMMARY

Blue cod (BCO), *Parapercis colias*, Rawaru

Characteristic	Details	Reference
Fishery	Predominantly an inshore pot fishery. The major commercial fisheries are off Southland and the Chatham Islands, with smaller but regionally significant fisheries off Otago, Canterbury, the Marlborough Sounds and Wanganui. Also the most important recreational fishery around South Island (taken primarily by line), and an important customary fishery.	MPI 2015a
Habitat	A demersal (epi-benthic) inshore species, often associated with rocky shores or reefs, including biogenic habitats (e.g., bryozoan reefs).	Batson & Probert 2000; Carbines 2004a; Morrison et al. 2014b
Distribution	Occurs in inshore waters around the New Zealand mainland, at the Chatham Islands, and on the western Chatham Rise at Mernoo Bank (although are most abundant south of Cook Strait).	Anderson et al. 1998
Stock structure	The stock structure of blue cod is unknown. However, tagging experiments suggest that blue cod populations may be isolated from each other and there may be several distinct populations within each Fisheries Management Area (FMA).	MPI 2015a
Depth range	Found from the shoreline to about 250 m. About 95% of the research catch (both trawl and potting methods) occurred between 5 and 140 m, with the mean depth being 35 m.	Anderson et al. 1998; Figure 8
Temperature range	Found in a relatively broad temperature range (95% interval 10–17 °C) with a mean at 13.2 °C.	Figure 8
Recruitment	Estimates of annual recruitment from stock modelling of the Southland stock between 1980 and 2010 indicate a relatively low level of between-year variation. Recruitment was perhaps better than average in 1990–92 and 1999. The causes of recruitment variation are unknown.	MPI 2015a
Reproduction	Blue cod have an annual reproductive cycle with an extended spawning season during late winter and spring, in inshore and mid shelf waters. Eggs are pelagic for about five days after spawning, and the larvae are pelagic for about five more days before settling onto the seabed.	
Growth	Growth may be influenced by a range of factors, including sex, habitat quality and fishing pressure relative to location. Size and age at sexual maturity also vary with location. In Northland, maturity is reached at 2 years, in the Marlborough Sounds at 3–6 years, and in Southland at 4–5 years. Blue cod are protogynous hermaphrodites, with individuals changing sex from female to male. Sex-change can occur in females over a broad size range. Males grow faster and become larger than females. The maximum recorded age is 32 years.	Carbines 1998, 2004a, b
Diet	Benthic teleosts appear to be the main prey category of blue cod, followed by crustaceans (mainly crabs, mysids and galatheids). Their diet is broadened, however, with bivalves, echinoderms, cephalopods, and gelatinous zooplankton.	Stevens et al. 2011
Possible climate change challenges	Blue cod may be indirectly affected by climate change influences on their biogenic habitats (i.e., sedimentation, ocean acidification, warming)	

STATE OF KNOWLEDGE SUMMARY

Bluefin Tuna, Pacific (TOR), *Thunnus orientalis*

Characteristic	Details	Reference
Fishery	Longline in New Zealand, along the east coast of the North Island and the south west coast of the South Island. In the Pacific region the majority of catches are taken in purse seine fisheries in the Western and Central Pacific Ocean. Pacific bluefin has been commercially fished in the New Zealand EEZ since at least 1960, with some catch likely but undocumented prior to that time. New Zealand catches are small compared to total stock removals globally. Recreational fishers make occasional catches of this species – e.g., record individual sizes have been taken on the WCSI. Listed as Vulnerable by CITES.	MPI 2016c; CITES 2013. Appendices I, II and III valid from 12 June 2013. UNEP
Habitat	A schooling species found in the epipelagic and mesopelagic zones	
Distribution	Occur broadly across the Pacific Ocean, especially the waters of the North Pacific Ocean. In New Zealand waters distribution is based on knowledge of the fishery. Abundant where the longline fishing effort is distributed along the east coast of the North Island and the south west coast of the South Island.	MPI 2016c
Stock structure	Believed to be a single Pacific-wide stock with part of the stock found within New Zealand waters. May have been confused by fishers with other blue fin species.	MPI 2016c
Depth range	1–200 m	FishBase
Temperature range	Tolerates ample temperature range but while it is possible to catch as far south as 48º S, few catches are made in the colder southern regions.	Collette & Nauen 1983; MPI 2016c
Recruitment	Recruitment estimates fluctuate widely without an apparent trend. Recent data points from the Japanese troll CPUE-based index of recruitment were at their lowest level since the start of the index (1980), but the 2016 recruitment suggested as being not particularly low.	MPI 2016c
Reproduction	Individuals found in New Zealand fisheries waters are mostly adults. Spawns only to the south of Japan and in the Sea of Japan.	Sund et al. 1981
Growth	Adult Pacific Bluefin reach a maximum size of 550 kg and lengths of 300 cm. Maturity is reached at 3 to 5 years of age and individuals live to 15+ years old.	MPI 2016c
Diet	A large pelagic predator of fish, crustaceans and cephalopods. Seen feeding on spawning hoki, WCSI.	MPI 2016c
Possible climate change challenges	May survive in larger numbers in more southern waters if temperatures increase. Food chain impacts to be considered in a high CO_2 world.	

STATE OF KNOWLEDGE SUMMARY

Bluefin Tuna, Southern (STN), *Thunnus maccoyii*

Characteristic	Details	Reference
Fishery	A longline fishery in New Zealand with fishing effort distributed along the east coast of the North Island and the south west coast of the South Island. The west coast South Island fishery predominantly targets southern bluefin tuna, whereas the east coast of the North Island fishery targets a range of species including southern bluefin tuna.	MPI 2016b; Matsuda et al. 1998
Habitat	A highly migratory species leading an oceanic, pelagic existence.	
Distribution	Global. In New Zealand fishing effort is distributed along the east coast of the North Island and the south west coast of the South Island where this species aggregates.	MPI 2016c
Stock structure	A single stock primarily distributed between 30º S and 45º S. Those caught in the New Zealand EEZ appear to represent the easternmost extent of a stock whose centre is in the Indian Ocean. Electronic tagging of juveniles showed that for a number of years tagged juveniles were not moving into the Tasman Sea. It was not known whether this was due to unfavourable environmental conditions or range contraction following the decline in the stock. However, in the last couple of years more of these tagged juveniles have been reported in New Zealand catches. Two sources of information suggest that there may be 'sub-structure' within the broader STN stock, in particular the Tasman Sea. If a particular year class was weak (or strong) when it initially recruited to the New Zealand fishery it remained so over time.	MPI 2016c
Depth range	From 50 - 2743 m.	FishBase
Temperature range	Temperate; 5°C - 20°C, prefer 16°C.	FishBase
Recruitment	Spawning stock biomass has declined from the 1950s to about 2012, but has since rebuilt, and is projected to continue rebuilding, as a result of strong recruitment of young fish.	MPI 2016c
Reproduction	Spawning recorded in the Indian Ocean south of Java. Adults are broadly distributed in the South Atlantic, Indian and western South Pacific Oceans, especially in temperate latitudes, and juveniles occur along the continental shelf of Western and South Australia and in high seas areas of the Indian Ocean. Two sources of information suggest that there may be 'sub-structure' within the broader STN stock, in particular the Tasman Sea. Individuals found in New Zealand fisheries waters are mostly adults.	MPI 2016c
Growth	Radiocarbon dating determined a life span of at least 30 years and that individuals reach asymptotic length at 20 years or older. Growth rate has changed over the course of the fishery and the size-at-maturity depends on when the fish was alive (prior to the 1970s, during the 1970s, or in the period since 1980), as well as which maturity ogive is used. e.g., a 12 year old fish could have a size at maturity of 159.4 cm or 165 cm.	Kalish et al. 1996; MPI 2016c
Diet	Apex pelagic predator, feeding opportunistically on a mixture of fish, crustaceans and squid and juveniles also feed on a variety of zooplankton and micronekton species.	Young et al. 1997

Possible climate change challenges	A change in spatial distribution of catches in the New Zealand region can be attributed more to the increase in domestic longline effort in the northern waters. A change in growth rate for juveniles and young adults has been attributed to a density dependent effect of overfishing, and though the species prefers a certain temperature environment, it is also found within a wide temperature range.

STATE OF KNOWLEDGE SUMMARY

Elephant Fish (ELE), *Callorhinchus milii*, Reperepe

Characteristic	Details	Reference
Fishery	A target or a bycatch species taken by bottom trawl or setnet. Elephant fish in ELE 5 (southern region) are taken by bottom trawl in fisheries targeted at flatfish and stargazer and some landings are taken by setnet in a fishery targeted mainly at school shark. From the 1950s to the 1980s, landings of elephant fish of around 1000 t $year^{-1}$ were common. Landings dropped considerably in the early 1980s but later increased to exceed 1000 t. The TACC for ELE 3, the largest bottom trawl fishery off the east coast of the South Island, has, with the exception of 2002–03, been consistently exceeded since 1986–87. The TACC is 1000 t in ELE 3 and 1304 t overall. Unreported discarded (and unreported catch) has been significant for this fishery. The discarded catch comprises smaller elephant fish, usually less than 50 cm FL. There is a customary and recreational take (low in numbers and/or data unavailable).	MPI 2017; MPI 2016b
Habitat	Elephant fish feed on benthic invertebrates on the continental shelf and upper continental slope. Mature elephant fish migrate to shallow inshore waters in spring and aggregate for mating. Eggs are laid on sand or mud bottoms, often in very shallow areas.	MPI 2017
Distribution	Uncommon off the North Island, although they occur south of East Cape on the east coast and south of Kaipara Harbour on the west coast. Most plentiful around the east coast of the South Island. Juveniles remain in shallow waters for up to 3 years.	MPI 2017
Stock structure	The six Quota Management Area (QMA) boundaries are related to the historical fishing pattern when this was a target fishery. Results from tagging studies conducted during 1966–69 indicate that elephant fish tagged in the Canterbury Bight remained in ELE 3. Separate spawning grounds to maintain each ‘stock’ have not been identified.	MPI 2017
Depth range	From 10 to 400 m, but most abundant in the shallow 10 to 30 m depths during spring-summer.	MPI 2017
Temperature range	Found in reasonably broad temperature range (95% interval 8.5–16.6 °C) with a median at 12.3 °C.	Figure 8
Recruitment	Research survey estimates of pre-recruit biomass are poorly determined for the WCSI but are high on the ECSI – a reflection of the larger numbers of smaller elephant fish found in the shallow strata. ECSI trawl survey pre-recruit (< 50 cm), recruited (50+ cm). The discarded catch from commercial fishing comprises elephant fish usually less than 50 cm FL. No evidence on the importance of sea temperature on recruitment but clearly juveniles prefer the warmer shallow waters.	MPI 2017
Reproduction	Mature elephant fish migrate to shallow inshore waters in spring and aggregate for mating. Eggs are laid in pairs (in large yellow-brown egg cases) on sand or mud bottoms, often in very shallow areas. The period of incubation is at least 5–8 months, and juveniles hatch at a length of about 10 cm FL. Females are known to spawn multiple times	MPI 2017

	per season. After egg laying the adults are thought to disperse and are difficult to catch; however, juveniles remain in shallow waters for up to 3 years.	
Growth	Relatively fast-growing. Males mature at a length of 50 cm FL at an age of 3 years, females at 70 cm FL at 4 to 5 years of age. The maximum age of elephant fish is unknown, however a tagged, 73 cm total length, Australian male was at liberty for 16 years, suggesting a longevity for males of at least 20 years (Coutin 1992, Francis 1997). Females probably also live to at least 20 years.	Coutin 1992; Francis 1997
Diet	Bottom feeders with a diet that consists almost entirely of shellfish and crustaceans – crabs and shrimps.	Fishingmag.co.nz
Possible climate change challenges	Water temperature is most likely a driver of juvenile abundance in the shallow water nurseries. Given their mainly southern distribution, the most likely impact will be a reduction in the suitability of northern South Island waters as nurseries. Diet may be affected through impacts of ocean acidification on prey.	

STATE OF KNOWLEDGE SUMMARY

Flat Oyster (OYS) *Ostrea chilensis*, Tio

Characteristic	Details	Reference
Fishery	Flat oysters (*Ostrea chilensis*), also known as dredge or Bluff oysters, occur throughout New Zealand, support highly valued fisheries and are candidate species for aquaculture. The Foveaux Strait oyster fishery (OYU 5) is the most substantial fishery in New Zealand. The Tasman Bay (OYS 7) fishery has declined markedly, and together with the Cloudy and Clifford Bays (OYS 7C) comprise smaller fisheries, with low landings. Oysters at the Chatham Islands (OYS 4) have limited potential for commercial exploitation. Start-up oyster aquaculture ventures occur in the Marlborough Sounds and Big Glory Bay Stewart Island. Farm production and revenue is thought to be low[*1]. The Foveaux Strait oyster fishery is a high-value, nationally important fishery that has harvested oysters for over 150 years. OYU 5 is targeted by customary, recreational, and commercial fishers; and is important to the socio-economics of Southland. Landings between 2010 and 2017 range from 9.5 to 13.2 million oysters, and the fishery is valued $20–30 million annually. Mortality of oysters from the parasite *Bonamia exitiosa* is a recurrent feature of the Foveaux Strait oyster population and the main driver of oyster abundance. Oyster mortality from *B. exitiosa* is considerably higher than the commercial catch. Typically, disease mortality kills 8–12% of the recruit-sized population annually, and up to 60% in some years, while fishers harvest less than 2% of this population. *B. ostreae* was recently identified in farmed oysters from Big Glory Bay, Stewart Island and will cause very high mortality in *O. chilensis* if it spreads to OYU 5.	MPI 2014; MPI 2016b; Michael et al. 2016. *1 No data publicly available on farm production figures and revenue.
Habitat	Flat oysters are benthic, epifaunal, sessile bivalve molluscs. *O. chilensis* occurs over a wide range of habitats and depth ranges in New Zealand. Oysters provide key roles in benthic communities and provide ecosystem services. Benthic habitats within the Foveaux Strait oyster fishery area comprise a variety of sand/gravel/shell flats and waves, rocky patch reef, and biogenic areas. Almost all fishing for oysters in Foveaux Strait occurs over gravel and gravel overlaid by calcareous sand substrates, with little other epifauna present. Oysters are found attached to hard substrates, especially in intertidal zones, and on a range of substrates from gravels to sandy mud. Benthic habitats in other oyster fisheries areas vary from areas of relatively high natural disturbance and gravel substrates (Cloudy/Clifford bays and the Chatham Islands) to fine sediment substrates typical of sheltered areas (Tasman Bay).	MPI 2016b; Michael 2007; Jones et al. 1994; Grabowski & Peterson 2007; Grabowski et al. 2012; Coen et al. 1999, 2007.
Distribution	*O. chilensis* have a New Zealand wide distribution. They are found from as far north as North Cape to south of Stewart Island. They are also found on the Chatham Islands.	MPI 2016b
Stock structure	Habitat driven morphological characteristics differ between fishery areas, but oysters are considered a single genetic stock. The Foveaux Strait oyster fishery (OYU 5) is managed as a single stock, and current stock assessments are	MPI 2016b

	undertaken in a fishery area defined by the 2007 survey area. There is likely to be larval dispersal and connectivity between localised populations within the fishery. Habitat driven morphological characteristics differ between fishery areas, but oysters are considered a single genetic stock. Relative to OYU 5, other stocks represent sparse scattered low density patches and low TACCs. Genetic structure between stocks is not described.	
Depth range	Found in intertidal to subtidal inshore waters, commonly in depths of down to 60 m.	MPI 2016b
Temperature range	8 °C to and up to 20°C (K Michael, NIWA, pers. comm.)	Bradford et al. 1991; Westerkov 1980
Recruitment	Recruitment to the OYU 5 fishery has been monitored annually since 2005 from spat monitoring, and 0+ and 1–2+ oysters landed as part of the commercial catch. Recruitment is highly variable-driven by between brooding-sized oyster density and a year effect that includes climate and biological factors. Most oyster spat surviving to post settlement are typically found on live flat oysters and, to a lesser extent, on shells of dead flat oysters or the circular saw *Astraea heliotropium* (Keith Michael, NIWA, pers. comm.).	
Reproduction	*O. chilensis* is a protandrous hermaphrodite, maturing first as males from 19 mm shell length (SL), and later as males and females ≥ 50 mm SL. In Foveaux Strait, only a small proportion (up to 12%) of the spawning population brood as females and 70–90% will develop male gonads. Oysters breed in the spring and summer in Foveaux Strait. There are no data on the spatio-temporal variation in the percentages of females brooding larvae within season, and drivers of this variation in wild populations. The percentage of the brooding size population varies with latitude, 12% in the south and up to 80% in lower latitudes around New Zealand. Larval development is aplanktonic (occurs inside the adult). In Foveaux Strait, larvae are brooded for 15–38 days depending on water temperature, and develop to pediveligers with eye spots), fully competent and ready to settle. As larval size increases with development, a small proportion of larvae may be released early (forced out of the pallial cavity by space limitation caused by growing larvae) and can continue to develop ex-parent. There is no information on the synchrony of larval release. with most larvae released within two hours, with few up to 48 hours after the first liberation in laboratory observations and in Foveaux Strait	MPI 2016b; Jeffs & Hickman 2000; Cranfield 1979; Hollis 1963; Stead 1971; Westerkov 1980; Cranfield & Michael 1989.
Growth	Growth rates of oysters vary between years and between areas of Foveaux Strait. Spat generally grow 5 to 10 mm in height by the winter after settlement. Mean height after one year is 18 to 25 mm, 25 to 35 mm after two years, 30 to 51 mm after three years, 40 to 65 mm after four years, and 65 to 75 mm after the fifth year. Oysters recruit to the legal-sized population at ages of 4–8 years. A legal-sized oyster will not pass through a 58 mm diameter ring, i.e., it must be at least 58 mm in the smaller of the two dimensions of height or length. There is evidence for strong seasonal variation in growth in all stocks.	Cranfield 1979
Diet	*O. chilensis* are active suspension feeders, consuming phytoplankton. Their diet is the same as or similar to that of many other suspension feeding taxa, including other bivalves.	MPI 2016b

Possible climate change challenges	*O. chilensis* occurs over a wide range of temperatures and environments. Its shells comprise 100% calcite. Although ocean acidification can cause larval mortality, the effects of ocean acidification on *O. chilensis* are uncertain. Larvae that are brooded are more protected in an acidifying ocean compared to their relatives employing broadcast spawning and pelagic larval development. Bivalves are able to regulate the water chemistry in the pallial cavity. The greatest risks of climate change, especially the increase in temperature is the effects of shellfish diseases. Bonamiosis in *O. chilensis* is known to be exacerbated by high seawater temperatures. Mortality in larvae and spat from disease can be high, but difficult to detect (e.g., Ostreid herpes virus (OsHV-1).	Lucey et al. 2015; Chaparro et al. 2009; Meseck et al. 2016; Przeslawski et al. 2015; Waldbusser et al. 2015; Rowley et al. 2014; Cole et al. 2016; Adlard et al. 2015; Engelsma et al. 2010; Hine 1997; Diggles et al. 2002.

STATE OF KNOWLEDGE SUMMARY

Green-lipped mussel (GLM), *Perna canaliculus,* Kuku, Kutai

Characteristic	Details	Reference
Fishery	Formerly a dredge fishery in the Hauraki Gulf and Tasman Bay, but fishing ceased in the 1960s in both areas owing to overexploitation. Now primarily an aquaculture species in enclosed bodies of water (e.g., Marlborough Sounds, Akaroa Harbour, Hauraki Gulf).	MPI 2015a
Habitat	Typically a bivalve of the lower shore and open coast. Common on rocky shores, but also able to form dense mats on sandy or shelly substrates.	MPI 2015a
Distribution	Distributed around mainland New Zealand, but most common in central and northern parts where it can form dense beds. It is absent from the Chatham Islands and other offshore islands.	MPI 2015a
Stock structure	Poorly understood. There appears to be strong genetic structuring, with northern and southern groups differentiated by frequency shifts in common haplotypes, and the occurrence of a unique haplotype in the South Island west coast population. The southern-northern population split occurs south of Cook Strait.	Apte et al. 2003
Depth range	Occurs from the mid-littoral to depths of over 50 m.	MPI 2015a
Temperature range	Environmental parameters, such as temperature and salinity, are strong determinants of the distribution of this species. Whilst its temperature range is from 5.3 °C in the south to 27 °C in the north, it appears to prefer the warmer waters of bays and estuaries in northern coastal areas. A wide range of salinities are tolerated, although the optimum range is 30 to 35.	Alfaro et al. 2001
Recruitment	There is little information on recruitment patterns. The aquaculture of the New Zealand greenshell mussel relies heavily on the production of spat by wild mussel populations. A significant amount of spat is sourced from Ninety Mile Beach. The origins of the spat washed up on this beach are unknown.	Alfaro et al. 2001
Reproduction	A dioecious (uni-sexual) broadcast spawner. Gonadal development takes place at water temperatures above 11°C and is related to food availability. Most spawning occurs in late spring to early autumn, but larvae can be present all year. Sexual maturity has been observed in some populations from 27 mm SL, with most individuals sexually mature by 40 mm SL. Maturity is reached in the first year, and females can produce up to 100 million eggs per season. Fertilisation is largely dependent on the proximity of adults.	Alfaro et al. 2001
Growth	Green-lipped mussels in suspended culture typically grow from 10 to 75 mm SL in six months, to 111–115 mm in one year, and to 195 mm in three and a half years. Growth is typically faster in cultured situations compared with natural beds, which are often overcrowded, are on exposed coasts, and are not constantly submerged so feeding is discontinuous. At Piha and West Tamaki Head, green-lipped mussel growth is variable, with individuals reaching 20–70 mm SL in their first year. Mussel yield can be predicted using remotely sensed environmental variables, but even more accurately using chemical and biological predictors collected locally to the mussel farming region. Particulate nitrogen is one of the most influential of the local predictors.	Zeldis et al. 2013; MPI 2015a

Diet	The larvae feed on phytoplankton, which may be supplemented with detritus, bacteria, and dissolved organic matter. The adults are filter-feeders, consuming phytoplankton, micro-zooplankton, and detritus.
Possible climate change challenges	Increase in suspended sediment could reduce feeding efficiencies. Ocean acidification could negatively impact shell growth and formation. International studies have shown that the strength of the proteinaceous byssal threads in mussels have been shown to weaken under OA (O'Donnell et al. 2013; Zhao et al. 2017)

STATE OF KNOWLEDGE SUMMARY

Hake (HAK), *Merluccius australis*, Kehe

Characteristic	Details	Reference
Fishery	Primarily taken by bottom trawl fishery (with a lesser midwater trawl component), either as a bycatch of hoki or as a target species.	MPI 2015a
Habitat	A bentho-pelagic species, primarily offshore.	
Distribution	Present on the entire New Zealand continental shelf (excluding the Bounty Plateau), but most abundantly around South Island. Juvenile hake have been taken in coastal waters on both sides of the South Island, in Tasman Bay, and on the Campbell Plateau.	Anderson et al. 1998; Colman 1998
Stock structure	There are three main hake spawning areas: off the west coast of the South Island, on the Chatham Rise and on the Campbell Plateau. Juvenile hake are found in all three areas. There are differences in size frequencies of hake between the west coast and other areas, and differences in growth parameters between all three areas. There is good evidence, therefore, to suggest that at least three separate stocks may exist in the EEZ.	Horn 1998, 2015
Depth range	Found from near-shore waters to about 1200 m. Most commercial fishery catches are in depths of 300–800 m, and 95% of the research trawl catch occurred between 200 and 880 m, with the mean depth being 640 m.	Hurst et al. 2000; Anderson et al. 1998; Figure 8
Temperature range	Found in a relatively broad temperature range (95% interval 6–13 °C) with a mean at 8.0 °C.	Figure 8
Recruitment	Year class strengths (YCS) vary moderately (but less than an order of magnitude) between years for all three stocks. The drivers of this variation are uncertain. Hake YCS on the Chatham Rise had a negative correlation with SOI and the Kidson (2000) 'Blocking' regime (characterised by a southwest-northeast contrast in rainfall: below normal in SW, above normal in NE). Hake YCS on the Campbell Plateau had a weak negative correlation with sea surface height.	Dunn et al. 2009a; Horn 2015
Reproduction	There are at least three main spawning areas for hake. The best known area is off the west coast of the South Island, where the season can extend from June to October, usually with a peak in September. Spawning also occurs to the west of the Chatham Islands during a prolonged period from at least September to January. Spawning on the Campbell Plateau, primarily to the northeast of the Auckland Islands, occurs from September to February with a peak in September–October. Spawning fish have been recorded occasionally on the Puysegur Bank and the western Chatham Rise.	Colman 1998; Horn 2015
Growth	Hake reach a maximum age of at least 25 years. Males, which rarely exceed 100 cm total length (TL), do not grow as large as females, which can grow to 120 cm TL or more. Chatham Rise hake reach 50% maturity at about 5.5 years for males and 7 years for females, Subantarctic hake at about 6 years for males and 6.5 years for females, and WCSI hake at about 4.5 years for males and 5 years for females. Juvenile hake reach a length of about 15–20 cm TL at one year old, and about 35 cm TL at 2 years.	Colman 1998; Horn 1997, 2008
Diet	Hake are demersal piscivores with a diet characterised by teleost fishes, mainly macrourids (e.g., javelinfish) and merlucciids (e.g., hoki). Squids and natant decapods are minor components of the diet.	Dunn et al. 2010a; Stevens et al. 2011

Possible climate change challenges	Year class strength is possibly influenced by SST, water circulation patterns, and sea surface height.

STATE OF KNOWLEDGE SUMMARY

Hoki (HOK), *Macruronus novaezelandiae*

Characteristic	Details	Reference
Fishery	Almost exclusively an offshore target trawl fishery, primarily using bottom trawl, but with a substantial midwater trawl component during the spawning season.	MPI 2015a
Habitat	A bentho-pelagic species, primarily offshore. Closer to the seabed during the day.	
Distribution	Present on the entire New Zealand continental shelf, particularly south of about 41° S. Large adult hoki are generally found deeper than 400 m, while juveniles are more abundant in shallower water. The major nursery ground for juvenile hoki aged 2–4 years is on the Chatham Rise, in depths of 200 to 600 m. The older fish disperse to deeper water and are widely distributed on both the Southern Plateau and Chatham Rise. A significant proportion of hoki move from the Chatham Rise to the Southern Plateau as they approach maturity, with most movement between ages 3 and 7 years.	Anderson et al. 1998; Livingston et al. 2002
Stock structure	Morphometric and ageing studies have found differences between adult hoki taken from the two main non-spawning areas (Chatham Rise and Southern Plateau), and from the two main spawning grounds in Cook Strait and off west coast South Island (WCSI). These differences suggest that there are two sub-populations of hoki. Whether or not they reflect genetic differences between the two sub-populations, or they are just the result of environmental differences between the Chatham Rise and Southern Plateau, is not known.	Horn & Sullivan 1996; Livingston & Schofield 1996; MPI 2015a
Depth range	Found from near-surface waters to about 1200 m. Commercial catches are most abundant in depths from 300 to 800 m. About 95% of the research trawl catch occurred between 240 and 730 m, with the mean depth being 430 m.	Hurst et al. 2000; Anderson et al. 1998; Figure 8
Temperature range	Found in a moderate temperature range (95% interval 6–12 °C) with a mean at 9.0 °C.	Figure 8
Recruitment	Variations in hoki recruitment between years (by about one order of magnitude) have considerable impact on this fishery. However, it is not clear to what extent (if at all) climate variability and oceanographic conditions influenced past hoki recruitment variability; a better understanding of this would be very useful for the future projection of stock size. Analyses in 2006 did not support previous conclusions that model estimates of recruitment to the western stock are strongly correlated with SOI. There was a correlation of -0.70 between the autumn SOI and annual estimates of recruitment (1+ and 2+ age classes) from the Chatham Rise trawl survey, but this was hard to interpret because the survey is an index of the combined recruitment to both the eastern and western stocks. A more recent analysis supports some climate effect on hoki recruitment but remains equivocal about its strength or form. Information on the ocean environment of the WCSI in relation to hoki and other spawning fisheries has been summarised and reviewed. Hypotheses about which variables drive hoki recruitment were presented, but an understanding of the underlying mechanisms and causal links between the WCSI marine environment and hoki year class survival remains elusive.	Livingston 2000; Bull & Livingston 2001; Francis et al. 2006; Dunn et al. 2009a; Bradford-Grieve & Livingston 2011

Reproduction	Hoki spawn from late June to mid-September, releasing multiple batches of eggs. Not all hoki within the adult size range spawn in a given year. The main spawning grounds are in Cook Strait, and off WCSI, with minor grounds at Puysegur and off the east coast South Island. Off WCSI, the planktonic eggs and larvae move inshore by advection or upwelling and are widely dispersed north and south with the result that 0+ and 1-year-old fish can be found in most coastal areas of the South Island and parts of the North Island.	Murdoch 1992; Parker et al. 2009; MPI 2015a, MPI 2017
Growth	Growth is fairly rapid with juveniles reaching about 27–35 cm total length (TL) at the end of the first year. Males appear to mature mainly from 60–65 cm TL at 3–5 years, while females mature at 65–70 cm TL. From the age of maturity the growth of males and females differs. Males grow up to about 115 cm TL, while females grow to a maximum of 130 cm TL. Fish from the eastern stock sampled in Cook Strait are smaller on average at all ages than fish from the WCSI. Maximum age is 20–25 years.	Horn & Sullivan 1996, MPI 2017
Diet	Hoki prey predominantly on euphausiids, mesopelagic fishes (mainly myctophids) and natant decapods (mainly pasiphaeid prawns). Squid and salps are minor prey components. An investigation into mesopelagic fish prey on the Chatham Rise over the period 2001 to 2009 showed no clear trend in their biomass, and no significant correlations with environmental indices (SST, sea surface height, chl-*a* concentration) were found.	McClatchie et al. 2005; Connell et al. 2010; Stevens et al. 2011; O'Driscoll et al. 2011
Possible climate change challenges	Year class strengths are possibly influenced by SST and SOI.	

STATE OF KNOWLEDGE SUMMARY

Jack mackerels (JMA), *Trachurus novaezelandiae, T. declivis, T. murphyi*, Hauture

Characteristic	Details	Reference
Fishery	The jack mackerel fisheries catch three species; two New Zealand species, *Trachurus declivis* and *T. novaezelandiae*, and *T. murphyi*, a species common in the south-east Pacific Ocean which appeared in New Zealand in the 1980s. There is a significant trawl fishery targeting jack mackerels off the lower west coast of North Island. Off northern New Zealand, the jack mackerel catch is largely taken by the purse seine fishery operating in the Bay of Plenty and on the east Northland coast. Apart from occasional trawling for jack mackerels on Chatham Rise, the remainder of landings is primarily a trawl bycatch.	MPI 2015a
Habitat	A bentho-pelagic species group. Ranges from near-shore to offshore shelf fringes.	
Distribution	*T. novaezelandiae* is abundant around North Island and in Tasman Bay. It is seldom found south of 45° S. *T. declivis* occurs on the coastal shelf around mainland New Zealand, and along the Chatham Rise. It is seldom found south of 49° S. *T. murphyi* occurs on the coastal shelf around South Island, along Chatham Rise, and off the southeast coast of North Island. It is seldom recorded south of 49° S or around the north and west of North Island. The invasion of *T. murphyi* into New Zealand waters in the mid-1980s coincided with increased frequency and magnitude of El Niño events.	Anderson et al. 1998; Taylor 2002
Stock structure	Unknown.	MPI 2015a
Depth range	Jack mackerels occur from near-shore waters to depths of over 600 m. The preferred ranges for each of the three species are much narrower, however. *T. novaezelandiae* occurs from near-shore to about 200 m, *T. declivis* is found in 60–350 m (although juveniles of this species do occur shallower), and *T. murphyi* occurs from 50 to about 600 m. Jack mackerels are presumed to be generally off the bottom at night, although surface schools can also be quite common during the day. Most of the commercial fishery catch is from waters 50–300 m deep.	Hurst et al. 2000; Anderson et al. 1998; Figure 8
Temperature range	The three species occur across a broad temperature range (95% interval 8–17 °C) with a mean at 13.0 °C. The preferences by species are much narrower, however. *T. novaezelandiae*, the shallowest species occurs commonly in a range from 12 to 17 °C, *T. declivis* from 11–14°C, and *T. murphyi* from 8–14 °C.	Figure 8
Recruitment	Year class strengths of *T. declivis* appear to be quite variable, but the drivers of this variation are unknown.	Horn et al. 2015
Reproduction	Jack mackerels have a protracted spring-summer spawning season. *T. novaezelandiae* and *T. declivis* probably matures at about 26–30 cm FL, which they attain at the age of 3–4 years, and 2–4 years, respectively. Spawning occurs in the North and South Taranaki bights, and probably in other areas as well. No spawning or successful juvenile recruitment of *T. murphyi* in New Zealand waters has been recorded.	Jones 1990
Growth	*T. novaezelandiae* and *T. declivis* have moderate initial growth rates that slow after about 6 years. Both species reach a maximum age of 25+ years. Age estimations of *T. murphyi* in New Zealand waters indicate that initial growth	Horn 1993; Taylor 2002

	is rapid, and slows at 6–7 years, with a maximum observed age of 32 years.	
Diet	Euphausiids are the dominant prey of all three *Trachurus* species, with amphipods and small teleosts of secondary importance. *T. murphyi* in New Zealand waters have also consume salps and galatheids.	Stevens et al. 2011
Possible climate change challenges	Krill (euphausiids), the main prey of all the *Trachurus* species, are potentially impacted by ocean acidification (as they are in Antarctica; Kawaguchi et al. 2013). Because the influx to New Zealand of the current stock of *T. murphyi* was probably climate-driven (coinciding with increased frequency and magnitude of El Niño events), there is potential for future influxes.	

STATE OF KNOWLEDGE SUMMARY

John dory (JDO), *Zeus faber*, Kuparu

Characteristic	Details	Reference
Fishery	A bottom trawl and Danish seine fishery, often taken as bycatch of the snapper, tarakihi, and trevally fisheries. Also taken by bottom pair trawl, bottom longline, mid-water and setnet fishing methods. A very important recreational and customary fishery. Highest catches in northwest North Island. Annual catches and fishing mortality have been relatively low over the last five years, and it is likely that recruitment has been low over the recent period (5–10 years). The rebuilding of the stock to the target biomass level will depend on an increase in the level of recruitment (from recent levels).	MPI 2016a
Habitat	An inshore demersal (epi-benthic) species occupying a wide range of habitats, including rocky and biogenic reefs, and areas of sand and mud bottom.	MPI 2016a
Distribution	Widespread, being found in the eastern Atlantic Ocean, the Mediterranean Sea and around Australia, Japan and New Zealand. Common in the inshore coastal waters of northern New Zealand, and to a lesser extent in Tasman Bay, in the northern South Island. In the Hauraki Gulf occasional feeding aggregations occur during winter. John dory appear to reach the southern limit of their range (due to cooler temperatures) off the north and northwest coasts of the South Island. Very few John dory are found on the southeast North Island south of Hawkes Bay, providing a gap between the east and west coast components.	MPI 2016a
Stock structure	John dory have been caught around most of the North Island and the northern South Island, indicating that the QMA boundaries (Figure 8, MPI 2016a) are not biologically appropriate. The analysis suggested five stocks around New Zealand: (1) Hauraki Gulf and east Northland; (2) Bay of Plenty; (3) west coast North Island; (4) southeast North Island; and (5) northern South Island. There is evidence to separate the Tasman Bay stocks from those to the north, including the occurrence of unusually large fish on the northern South Island.	MPI 2016a; Dunn & Jones 2013
Depth range	Found in depths down to 300 m, but most commonly in inshore coastal depths of <50 m.	MPI 2016a
Temperature range	Found in a broad temperature range (95% interval 11.5–18 °C) with a median at 13 °C and maximum of 23 °C. Relatively warm water extends further down the west coast of the South Island but it seems unlikely that John dory stocks will permanently occur further south than about 42° S under current oceanographic conditions. In the Mediterranean Sea, John dory have a preference for waters warmer than 16.5 °C.	Figure 8; Beentjes & Stevenson 2001; Maravelias et al. 2007
Recruitment	There is variation in recruitment in some areas. In the northern North Island region it is likely that recruitment has been low over the recent period (5–10 years). The rebuilding of the stock to the target biomass level will depend on an increase in the level of recruitment (from recent levels). West coast South Island research survey estimates of pre-	MPI 2016a

	recruit biomass for the last four trawl surveys (2009, 2011, 2013 and 2015) have estimated the recruited biomass to be at the highest level of the entire 4 year time series. The 2015 estimate is the highest and the strong 1+ cohort visible in length frequencies suggests the biomass will remain high, at least in the short term.	
Reproduction	Serial spawners (spawning more than once in a season). The time of spawning varies substantially, occurring between December and April on the North Island northeast coast. It seems likely that there is at least occasional spawning around much of the North Island. It is unclear whether spawning is really absent north of Hauraki Gulf because of the sparse sampling of this area. The eggs are large and pelagic, taking 12–14 days to hatch. Spawning fish and nursery grounds are found in all five stocks. Females mature at a size of 29 to 35 cm standard length and in general, larger females mature earlier in the season and are more fecund. Males mature at 23 to 29 cm standard length.	MPI 2016a; Hore 1982
Growth	Initially John dory grow rapidly with both males and females reaching 12 to 18 cm standard length after the first year. From the second year onwards females grow faster than males and reach a greater maximum length. Maximum age is 12 years.	
Diet	Primarily a piscivore; eats a variety of fish, especially schooling fish, also occasionally squid.	
Possible climate change challenges	Currently there is no evidence to suggest that temperatures are driving low recruitment in the north and high recruitment in the south. Catch data suggest that John dory stocks may have shifted southward in around 2000, and then the fishery on the WCSI in JDO 7 increased in subsequent years. It may be that fish from JDO 2 (the west coast of the north Island and east coast of the North Island) ‘seeded’ the JDO 7 fishery at around that time. Because John dory are at the southern limit of their range on the north coast of the South Island, it seems likely that stock size and distribution, and so commercial catches in JDO 7, will have a pronounced response to climatic conditions and be more variable than catches around the northern North Island.	

STATE OF KNOWLEDGE SUMMARY

Kahawai (KAH), *Arripis trutta*

Characteristic	Details	Reference
Fishery	Purse seine vessels take most of the commercial kahawai catch, sometimes targeted, but more often as a bycatch of other targeted surface-schooling species (e.g., skipjack). Substantial quantities are also taken seasonally in set net fisheries and as a bycatch in longline and trawl fisheries. Also a very important recreational and customary species.	MPI 2015a
Habitat	A bentho-pelagic inshore species often occurring in large schools near the surface. They occur mainly in coastal seas, harbours and estuaries and will enter the brackish water sections of rivers. Juveniles (0+) are often present in estuaries or enclosed bays and over eelgrass meadows (*Zostera* spp.).	
Distribution	Occurs in inshore waters around the New Zealand mainland, north of 45° S. Most abundant off northern North Island.	Anderson et al. 1998
Stock structure	There may be two stocks of kahawai within New Zealand waters with centres of concentration around the Bay of Plenty and the northern tip of South Island. There is some (limited) mixing between these areas.	Smith et al. 2008
Depth range	Found from the shoreline to about 150 m. Most commercial fishery catch is taken by purse seine in surface waters. About 95% of the research trawl catch occurred between 10 and 80 m, with the mean depth being 30 m.	Anderson et al. 1998; Figure 8
Temperature range	Found in a relatively broad temperature range (95% interval 12–19 °C) with a mean at 13.5 °C.	Figure 8
Recruitment	No information is available on recruitment mechanisms or variation.	
Reproduction	The spawning habitat of kahawai is unknown but is thought to be associated with the seabed offshore. Schools of females with running ripe ovaries have been caught by bottom trawl in 60–100 m in Hawke Bay; most running ripe fish were observed from January to April. Sexual maturity in males occurs at around 39 cm FL and in females at 40 cm (i.e., ~4 years). Eggs have been found in February in the outer Hauraki Gulf.	Jones et al. 1992
Growth	Kahawai grow rapidly, attaining a length of around 15 cm at the end of their first year, and maturing after 3–5 years at about 40 cm, after which their growth rate slows. Male and female growth curves are broadly similar. The maximum recorded age is 26 years.	Stevens & Kalish 1998
Diet	Kahawai consume epi-benthic and pelagic crustaceans (e.g., copepods, euphausiids, and mysids) and teleosts (e.g., sprats, mullet, larval fishes, and smaller kahawai). Kahawai smaller than 10 cm mainly eat copepods. Although principally pelagic feeders, they will also take food from the seabed.	Stevens et al. 2011
Possible climate change challenges	Modifications to estuaries or enclosed bays frequented by juveniles (e.g., by increased sedimentation resulting from elevated rainfall, or changes to flora and fauna as a consequence of physical or climatic changes) could impact recruitment by altering food sources or preferred habitats.	

STATE OF KNOWLEDGE SUMMARY

Ling (LIN), *Genypterus blacodes*, Hoka

Characteristic	Details	Reference
Fishery	Primarily a major bycatch species in the bottom trawl fishery for hoki, but occasionally taken as a trawl target. There is also a significant target bottom longline fishery.	MPI 2015a
Habitat	An almost exclusively benthic offshore species.	
Distribution	Present on the entire New Zealand continental shelf, particularly south of about 41° S. Little is known about the distribution of juveniles smaller than about 40 cm TL, when they begin to appear in trawl samples over most of the adult range.	Anderson et al. 1998
Stock structure	There are at least five ling stocks, i.e., WCSI, Chatham Rise, Cook Strait, Bounty Plateau, and the Southern Plateau (including the Stewart-Snares shelf and Puysegur Bank). Stock affinities of ling north of Cook Strait are unknown.	Horn 2005
Depth range	Found from about 30 to 850 m. Most commercial fishery catches are in depths of 200–600 m, and 95% of the research trawl catch occurred between 100 and 710 m, with the mean depth being 470 m.	Hurst et al. 2000; Anderson et al. 1998; Figure 8
Temperature range	Found in a relatively broad temperature range (95% interval 6–13 °C) with a mean at 8.0 °C.	Figure 8
Recruitment	Between-year recruitment variability in all ling stocks (except on Bounty Plateau) is low. The drivers of any variability are unknown.	MPI 2015a
Reproduction	Ling in spawning condition have been reported in a number of localities throughout the EEZ. Time of spawning appears to vary between areas: August to October on the Chatham Rise; September to December on Campbell Plateau and Puysegur Bank; September to February on the Bounty Plateau; July to September off WCSI and in Cook Strait.	Horn 2005
Growth	The maximum recorded age is 46 years, although few fish live longer than 30 years. A growth study of ling from five areas (west coast South Island, Chatham Rise, Bounty Plateau, Southern Plateau, and Cook Strait) showed that females grew significantly faster and reached a greater size than males in all areas, and that growth rates were significantly different between areas. Ling grow fastest in Cook Strait and slowest on the Southern Plateau.	Horn 2005
Diet	Ling are a benthic generalist, with a diet characterised by benthic crustaceans, mainly *Munida gracilis* and *Metanephrops challengeri*, and demersal fishes, mainly Macrourids and scavenged offal from fishing vessels. Squid are a minor prey component.	Dunn et al. 2010a; Stevens et al. 2011
Possible climate change challenges	No known challenges.	

STATE OF KNOWLEDGE SUMMARY

Orange roughy (ORH), *Hoplostethus atlanticus*

Characteristic	Details	Reference
Fishery	A deepwater trawl fishery, using bottom or near bottom trawls.	MPI 2015a
Habitat	Epi-benthic deepwater.	
Distribution	Present around the margin of the entire New Zealand continental shelf, but particularly abundant on Chatham Rise, off southeast North Island, and the southwestern Challenger Plateau. Adult orange roughy form aggregations both during and outside the spawning period. Juveniles have been found in large numbers in only one area, at a depth of 800–900 m about 150 km east of the main spawning ground on the north Chatham Rise.	Anderson et al. 1998
Stock structure	There are believed to be several stocks of orange roughy in the New Zealand EEZ, based on the presence of multiple spawning grounds, genetic analyses, and the distribution of relatively distinct population concentrations.	MPI 2015a
Depth range	Found from about 700 to at least 1500 m. Most commercial fishery catches are in depths of 800–1200 m, and 95% of the research trawl catch occurred between 770 and 1070 m, with the mean depth being 880 m.	Hurst et al. 2000; Anderson et al. 1998; Figure 8
Temperature range	Found in a relatively narrow temperature range (95% interval 5–9 ºC) with a mean at 6.7 ºC.	Figure 8
Recruitment	The limited age-frequency data available indicate that orange roughy populations experience periods of above or below average recruitment success. The reasons for this are unknown.	Dunn et al. 2009b
Reproduction	Spawning occurs once each year between June and early August in several areas within the New Zealand EEZ, from the Bay of Plenty in the north, to the Auckland Islands in the south. Spawning occurs in dense aggregations at depths of 700–1000 m and is often associated with bottom features such as pinnacles and canyons. Spawning fish are also found outside the EEZ on the Challenger Plateau, Lord Howe Rise, and Norfolk Ridge to the west, and the Louisville Ridge to the east. The eggs are large (2–3 mm in diameter), are fertilised in the water column, and then drift upwards towards the surface and remain planktonic until they hatch close to the bottom after about 10 days. Details of larval biology are poorly known.	Pankhurst 1988; Zeldis et al. 1994
Growth	Orange roughy are slow-growing and long-lived fish that may live up to 130 years or more. Maximum size appears to vary among local populations. Their otoliths have a marked transition zone in banding which is believed to be associated with the onset of maturity. The estimates of mean age at the transition-zone vary between grounds in the New Zealand EEZ, ranging from 23 to 31.5 years.	Mace et al. 1990; Horn et al. 1998; Andrews et al. 2009
Diet	Orange roughy has an opportunistic predatory strategy with a broad diet dominated by prawns and mesopelagic teleosts, but with substantial components of mysids and cephalopods. There were ontogenetic changes in prey; smaller fish (up to 20 cm) ate more crustaceans whilst larger fish (31 cm and above) ate more teleosts and cephalopods.	Stevens et al. 2011; Forman et al. 2016
Possible climate change challenges	Changes in circulation patterns could influence the distribution of eggs in their pelagic phase.	

STATE OF KNOWLEDGE SUMMARY

Oreo, Black (BOE), *Allocyttus niger*

Characteristic	Details	Reference
Fishery	A deepwater bottom trawl fishery.	MPI 2015a
Habitat	Epi-benthic deepwater.	
Distribution	Significant concentrations occur primarily on Chatham Rise, off southeast of South Island, and at Puysegur Bank. Its distribution south of about 45° S is not well known. Juveniles have a pelagic phase lasting for 4–5 years (i.e., to about 23 cm TL). Black oreo appear to settle over a wide range of depths on the south Chatham Rise but appear to prefer to live in the depth interval 600–800 m that is often dominated by individuals with a modal size of 28 cm TL.	Anderson et al. 1998
Stock structure	A variety of techniques (i.e., genetic, lateral line scale counts, settlement zone counts, parasites, otolith microchemistry, and otolith shape) have been used to examine stock structure of New Zealand black oreo. While some differences between areas were apparent, inconsistencies did not allow the development of an unequivocal stock structure.	MPI 2015a
Depth range	Found from about 550 to 1300 m. Most of the commercial catch is taken between 650 and 1200 m. About 95% of the research trawl catch occurred between 670 and 1100 m, with the mean depth being 960 m.	Hurst et al. 2000; Anderson et al. 1998; Figure 8
Temperature range	Found in a moderate temperature range (95% interval 3–8 °C) with a mean at 6.0 °C.	Figure 8
Recruitment	No information on recruitment variability is available.	
Reproduction	Spawning occurs from late October to at least December and is widespread on the south Chatham Rise. Mean length at maturity for females is 34 cm TL.	
Growth	They are slow-growing and long-lived with a maximum age estimated to be about 150 years. Estimated age at maturity for females was 27 years.	Neil et al. 2008
Diet	Black oreo consume mainly salps and hyperiid amphipods, and to a lesser extent fish, prawns, mysids, copepods and squids. It exhibits significant ontogenetic variation in diet; there is a decrease in salps, amphipods and copepods, and an increase in prawns and fish, as predator size increases. The relative importance of prey may vary slightly between areas: crustaceans and salps were more important on Chatham Rise than off southern New Zealand, and teleosts and cephalopods were more important off southern New Zealand.	Stevens et al. 2011; Forman et al. 2016
Possible climate change challenges	Consumes a relatively narrow diet, so would be impacted by changes in salp abundance and distribution. Juveniles have a near-surface pelagic phase, so their distribution could be influenced by changes in water circulation patterns.	

STATE OF KNOWLEDGE SUMMARY

Oreo, Smooth (SSO), *Pseudocyttus maculatus*

Characteristic	Details	Reference
Fishery	A deepwater bottom trawl fishery.	MPI 2015a
Habitat	Epi-benthic deepwater.	
Distribution	Significant concentrations occur on the south Chatham Rise, along the east coast of the South Island, the north and east slope of Pukaki Rise, the Bounty Plateau, the Snares slope, Puysegur Bank and the northern end of the Macquarie Ridge. Its distribution south of about 45° S is not well known. The juveniles probably do not have a pelagic phase.	Anderson et al. 1998
Stock structure	A variety of techniques (i.e., genetic, lateral line scale counts, settlement zone counts, parasites, otolith microchemistry, and otolith shape) have been used to examine stock structure of New Zealand smooth oreo. Some differences between areas were apparent, indicating that southern and western fish were distinct from those on the Chatham Rise, and also that there might be some stock distinction within the Chatham Rise.	MPI 2015a
Depth range	Found from about 550 to 1400 m. Most of the commercial catch is from depths between 800 and 1300 m. About 95% of the research trawl catch occurred between 800 and 1200 m, with the mean depth being 1000 m.	Hurst et al. 2000; Anderson et al. 1998; Figure 8
Temperature range	Found in a relatively narrow temperature range (95% interval 3–8 °C) with a mean at 4.8 °C.	Figure 8
Recruitment	No information on recruitment variability is available.	
Reproduction	Spawning occurs from late October to at least December and is widespread on the south Chatham Rise in small aggregations. Mean length at maturity for females is 40 cm TL.	
Growth	Unvalidated age estimates indicate that smooth oreo is slow growing and long lived. Maximum age is estimated to be around 90 years. Estimated age at maturity for females is 31 years.	Neil et al. 2008
Diet	Smooth oreo is strongly specialised on gelatinous zooplankton (jellyfish, salps and coelenterates). Other dietary components are mesopelagic teleosts and cephalopods. It does not exhibit strong ontogenetic variation in diet, but teleosts may be more important to larger fish.	Stevens et al. 2011; Forman et al. 2016
Possible climate change challenges	Consumes a relatively narrow diet, so would be impacted by changes in salp and jellyfish abundance and distribution.	

STATE OF KNOWLEDGE SUMMARY

Pāua (PAU), *Haliotis iris*, *H. australis*

Characteristic	Details	Reference
Fishery	Commercial catches of pāua are gathered by hand while free diving (use of underwater breathing apparatus is not permitted except at the Chatham Islands). Virtually the entire commercial fishery is for the black-foot pāua, *H. iris*, with a minimum legal size of 125 mm SL[1]. Yellow-foot pāua, *H. australis*, are less abundant than *H. iris*, caught only in small quantities, and have a minimum legal size of 80 mm[1]. The New Zealand abalone fishery is the 3rd largest wild caught abalone fishery world-wide[2] and had an export value of NZ$36,445,695 for the 2017 calendar year[3]. There is also a large recreational fishery, customary, and illegal fishery, and the shells are used extensively for decorations and jewellery.	MPI 2015a; FAO 2011; New Zealand Seafood Exports 2017
Habitat	Intertidal and subtidal rocky reefs. Juveniles inhabit the undersides of cobbles and boulders[4], presumably for protection against dislodgement by wave action and predation. Adult pāua can form large aggregations on reefs in shallow subtidal coastal habitats. There may be a negative association between pāua and kina, although pāua have recently been shown to displace sea urchins from shallow water wave-sheltered habitats in the absence of fishing pressure. At high densities, kina also appear to exclude pāua from the reef.	Andrew & MacDiarmid 1999; MPI 2015a; Will et al. 2015; Schiel 1989; 1993 McShane et al. 1995;1996; Wing et al. 2015; Naylor & Gerring 2001
Distribution	Around mainland New Zealand and its offshore islands (i.e., North, South, Stewart and Chatham islands); most abundant south of the Wairarapa coast, and especially south of Cook Strait. Distribution spans nearly 20 degrees of latitude. Movement of post-larval (juvenile and adult) individuals is over a sufficiently small spatial scale that the species may be considered sedentary.	MPI 2015a; Schiel & Breen 1991; McShane et al. 1994
Stock structure	There are high levels of genetic variation within samples of *H. iris* taken from locations spread throughout New Zealand. There are also two patterns of weak but significant population genetic structure. Firstly, individuals from the Chatham Islands are genetically distinct to those from mainland New Zealand (most likely due to isolation by distance). Southern North Island individuals are more similar to South Island than to those from other North Island locations (corresponding with major oceanographic features at Cook Strait and East Cape) .	Will et al. 2011; 2015
Depth range	From the intertidal zone to 20 m, although they tend to be shallower than 10 m, and concentrated in 4–5 m depth.	New Zealand Pāua Industry Council, pers. comm., Nov 2018.
Temperature range	Pāua are found in waters between about 9 ºC and 21 ºC.	Naylor et al. 2006
Recruitment	Abalone recruitment is very localised, occurring close to the spawning stock. The pelagic larval phase is short (<10 days). Habitat related factors are an important source of variation in the post-settlement survival of pāua. Recruitment can vary over short distances and may be influenced by factors such as wave exposure, habitat structure, availability of	Babcock & Keesing 1999 (modelled for *Haliotis laevigata*); Tong et al. 1992

	suitable settlement surfaces and food, and population density.	
Reproduction	Pāua mature at a ~60–90 mm SL, with decreased length at maturity noted in warmer waters. Pāua are broadcast spawners and usually spawn once a year, often in late summer or autumn. Abalone spawning success is contingent on having good concentrations of adults, with adults <1 m apart. Spawning has been linked with the first large southerly storm at the end of summer.	New Zealand Pāua Industry Council, pers. comm. Nov 2018; Naylor et al. 2006; McShane & Naylor 1996; Babcock & Keesing 1999 (as modelled for *Haliotis laevigata*); G. Moss (NIWA) pers. comm.
Growth	Growth can vary over short distances (e.g., between exposed headlands and sheltered bays as little as <200 m apart[1], possibly due to food availability) and may be influenced by factors such as temperature, wave exposure, habitat structure, availability of food and population density. Water temperature (SST) is an important determinant of growth rate and maximum size. The relationship between pāua growth and temperature is very size-dependent. Pāua juveniles in aquaria grow more rapidly at warmer temperatures with the optimal temperature for growth varying with juvenile size. The critical thermal maximum of pāua (a measure of thermal tolerance) is greater in smaller juveniles. For adult pāua in the wild, fastest growth was noted in areas with lower mean monthly maximum SST, and slowest growth in areas with the highest mean monthly maximum SST. Size at maturity decreased with increasing temperature and appears to be slower in areas where the maximum sea surface temperature is above about 17°C. Lower oxygen levels reduce the growth rates of Australian abalone. In the laboratory growth of juveniles is significantly reduced under elevated pCO_2 (lowered pH).	Naylor et al. 2006; McShane & Naylor 1995; Tong 1980;1982; Cummings et al. 2019; Searle et al. 2006. Harris et al. 1999; Cunningham et al. 2016
Diet	Pāua feed preferentially on drift algae. Effects on their preferred macroalgal food (e.g., die off under elevated temperatures) can result in starving pāua (e.g., recently observed at the Chatham Islands).	New Zealand Pāua Industry Council, pers. comm.
Possible climate change challenges	Challenges include ocean acidification, ocean warming and sedimentation[1] which, combined with varying food quantity and quality, can affect abalone survivorship, growth, and reproduction and susceptibility to disease. Studies on the *Haliotis* genus have reported effects of ocean acidification and warming on larval survival and development but not on fertilisation success. *H. iris* larval development is negatively affected by ocean acidification, and positively influenced by temperature. Warming and acidification similarly affect growth of *H. iris* juveniles. Juveniles grow more rapidly at warmer temperatures and thermal tolerance in juveniles declines with size. While survival of juvenile pāua was not always affected by ocean acidification, dissolution of the shell surface was evident, and growth was significantly reduced in summer (but not winter) temperatures.	AFL 2014; Vilchis et al. 2005; Rogers-Bennett et al. 2007, 2010; Byrne et al. 2011; Crim et al. 2011; Byrne et al. 2010; Cummings et al. 2019; Tong et al. 1992; Cunningham et al. 2016; Tong 1980; 1982; Searle et al. 2006; Chew et al. 2013; Sainsbury 1982;

	Egg, and especially sperm production of red abalone was highly sensitive to warm water, especially when combined with starvation.	Phillips & Shima 2006
	Warming seas can negatively impact survival of the major pāua food source, macroalgae (e.g. through altering nutrient availability). Increased occurrence of extreme weather events will likely result in more coastal sedimentation, resulting in deposition of sediment and elevation of water column suspended sediment concentrations. Juvenile pāua can avoid sedimentation-related smothering by moving to vertical surfaces on cobble edges. In boulder-silt habitat, burial by localised shifts in sand during storms can be a major cause of death of adult pāua. Elevated suspended sediment concentrations can increase mortality of larval pāua in the water column. It can also affect pāua of all ages through limiting of light levels required for growth of macroalgae (preferred food), and by reducing cover of crustose coralline algae (and thus available habitat) for recruitment. Anecdotally, pāua fishers report seeing more storm events, localised die-off of brown algae, increased sedimentation, and reduced pāua recruitment.	

STATE OF KNOWLEDGE SUMMARY

Red cod (RCO), *Pseudophycis bachus*, Hoka

Characteristic	Details	Reference
Fishery	Primarily an inshore trawl fishery off South Island, where it is often targeted, particularly off the southeast coast. The fishery is seasonal, usually from November to June, with peak catches around January and May. Also a bycatch in inshore bottom longline fisheries.	MPI 2015a
Habitat	Almost exclusively demersal inshore.	
Distribution	Occurs around the entire New Zealand mainland coastal shelf, and on the Chatham Rise and Auckland Islands shelf, but is most abundant around South Island. They are seasonally abundant, with schools appearing in the Canterbury Bight and Banks Peninsula area around November. These schools are feeding aggregations and are not found in these waters after about June. Catch data indicate that they move into deeper water after this time.	Anderson et al. 1998; MPI 2015a
Stock structure	Unknown.	MPI 2015a
Depth range	Found from the shoreline to at least 700 m. Most commercial fishery catches are in depths of 20–200 m, and 95% of the research trawl catch occurred between 20 and 330 m, with the mean depth being 100 m.	Hurst et al. 2000; Anderson et al. 1998; Figure 8, this report
Temperature range	Found in a broad temperature range (95% interval 8–16 °C) with a mean at 11.4 ºC.	Figure 8, this report
Recruitment	The fishery is characterised by large variations in catches between years due to highly variable recruitment. An inverse relationship between year class strength (YCS) and SST off the east, south and west coasts of South Island has been shown.	Beentjes & Renwick 2001; Dunn et al. 2009a
Reproduction	The start of the spawning season occurs later as latitude increases. In the Canterbury Bight, spawning occurs from August to October. No definite spawning grounds have been identified on the southeast coast, but there is some evidence that red cod spawn in deeper water (300–750 m). Juvenile red cod are found in offshore waters after the spawning period; however, no nursery grounds are known for this species.	Habib 1975; MPI 2015a
Growth	Fast-growing, short-lived species with few fish older than six years.	Horn 1996
Diet	Primarily benthic crustaceans (particularly galatheids and pandalid shrimps) and benthic teleosts (particularly opalfish, dwarf cod, tarakihi and red cod), but does consume a wide range of benthic animals and salps.	Stevens et al. 2011; Horn et al. 2012
Possible climate change challenges	Successful recruitment appears to be dependent on cool SSTs.	

STATE OF KNOWLEDGE SUMMARY

Red gurnard (GUR), *Chelidonichthys kumu*, Kumukumu

Characteristic	Details	Reference
Fishery	A major bycatch species of inshore trawl fisheries in most areas of the New Zealand region, particularly red cod and flatfish. There are also some minor target trawl fisheries in some areas. A small proportion of the total red gurnard catch is taken by bottom longline and set net. Also a relatively important recreational and customary species.	MPI 2015a
Habitat	Almost exclusively demersal inshore.	
Distribution	Occurs around the entire New Zealand mainland coastal shelf, and at the Chatham Islands, though not present south of Stewart Island. Small juveniles (0+ year class) appear to prefer shallow enclosed embayments.	Anderson et al. 1998
Stock structure	Unknown.	MPI 2015a
Depth range	Found from near-shore to about 300 m. Most of the commercial catch and about 95% of the research trawl catch occurred between 15 and 120 m, with the mean depth being 40 m.	Hurst et al. 2000; Anderson et al. 1998; Figure 8
Temperature range	Found in a relatively broad temperature range (95% interval 11–18 °C) with a mean at 13.5 °C.	Figure 8
Recruitment	Year class strengths (and total biomass) can vary markedly between years, but the reasons for this are not clear.	MacGibbon & Stevenson 2013; MPI 2015a
Reproduction	Red gurnard have a long spawning period through spring and summer with a peak in early summer. Spawning grounds appear to be widespread, although are perhaps localised over the inner and central shelf. Egg and larval development take place in surface waters.	Elder 1976
Growth	Growth rate varies with location, and females grow faster and are usually larger at age than males. Red gurnard reach sexual maturity at an age of 2–3 years and a FL of about 23 cm, after which the growth rate slows. Maximum age is about 16 years.	Elder 1976
Diet	Crustaceans (mainly galatheids and crabs) comprise most of the diet, although teleost fish (often red cod) are also important. Polychaetes are also eaten. No marked ontogenetic changes in diet are apparent.	Stevens et al. 2011
Possible climate change challenges	Significant correlations between estimated abundance and some climatic variables have been noted for some red gurnard stocks (Dunn et al. 2009a). North-western gurnard abundance was negatively related to SST and SOI, whereas south-western abundance was positively related to SOI and negatively related to a high frequency of southerly winds. North-eastern gurnard abundance was positively related to a dominance of wet, cool weather in the south of New Zealand. Given the above correlations, elevated surface temperatures may influence eggs and larvae which are found in surface waters.	

STATE OF KNOWLEDGE SUMMARY

Rig (SPO), *Mustelus lenticulatus*, Pioke, Makō

Characteristic	Details	Reference
Fishery	Rig are caught in coastal waters throughout New Zealand during spring and summer, when they aggregate inshore. A large proportion is taken by trawlers as bycatch, when targeting species such as gurnard, tarakihi, and snapper, as well as in bottom setnet fisheries that target rig, school shark, flatfish, red cod, spiny dogfish and elephant fish. The total rig landing 2014/15 was 1,413 tonnes. Rig are the most commonly recreationally caught shark in New Zealand (Wynne-Jones et al. 2014). Recreational catches are estimated (about 6 t were accounted for in 2012), however unknown quantities of juvenile rig are caught by set-nets placed in harbours and shallow bays. Māori fishers traditionally caught large numbers of "dogfish" during the last century and early this century. Rig was probably an important species, although spiny dogfish and school shark were also taken. The historical practice of having regular annual fishing expeditions, during which thousands of dogfish were sun-dried on wooden frames, is no longer prevalent. However, rig are still caught in small quantities by customary non-commercial fishers in parts of the North Island, especially the harbours of the Auckland region.	MPI 2016b
Habitat	A demersal species of coastal and continental shelf waters, harbours and shallow bays.	MPI 2016b; Francis 2013a; Jones et al. 2015
Distribution	Trawl catches occur all around mainland New Zealand. Set net catches are greatest in North and South Taranaki Bight, Tasman Bay/Golden Bay, Canterbury Bight, and Foveaux Strait/Stewart Island. Young are generally born in shallow coastal waters, especially in harbours and estuaries, throughout North and South Islands. They grow rapidly during their first summer, and then disappear as water temperatures drop in autumn–winter. They presumably move into deeper water.	MPI 2016b
Stock structure	Boundaries between biological stocks are poorly defined. Most male rig remain within the quota management areas shown in Figure 8, whereas females tend to move gradually to adjacent FMAs.	Francis 2010; MPI 2016b
Depth range	Most of the catch is taken in water less than 50 m deep during spring and summer, when rig aggregate inshore.	MPI 2016b
Temperature range	Found in a broad temperature range (95% interval 9.0–18 °C) with a median at 13.4 °C.	Figure 8, this report
Recruitment	East Coast South Island length-frequency distributions from inshore trawl survey strata in 2012 and 2014 indicated strong recruitment in recent years. The size composition of the WCSI trawl survey catches also suggests strong recruitment in recent years.	MPI 2016b
Reproduction	Rig give birth to young during spring and summer following a 10–11 month gestation period. Most females breed annually. The number of young produced increases exponentially with the length of the mother, and ranges from 2 to 37 (mean about 11). The young grow rapidly during their first summer.	Francis & Mace 1980
Growth	Rig are born at a TL of 25–30 cm. On the South Island male and female rig attain maturity at 5–6 years (about 85 cm) and 7–8 years (about 100 cm), respectively (Francis &	Francis & Ó Maolagáin 2000; Francis & Francis

	Ó Maolagáin 2000). Rig in the Hauraki Gulf mature earlier – 4 years for males and 5 years for females – and at smaller sizes (Francis & Francis 1992 a, b). Longevity is about 20 years.	1992a, b
Diet	Rig feed mainly on benthic invertebrates, particularly crustaceans and worms.	King & Clark 1984
Possible climate change challenges	A change in water temperature might affect the seasonal inshore/offshore movements of adults (which aggregate in shallow water during spring) and juveniles (which leave estuaries and bays in winter). Increased temperatures and ocean acidification might impact on the abundance of crabs, which are the main component of the diet of rig. Modifications to estuaries or enclosed bays frequented by juveniles (e.g., by increased sedimentation resulting from elevated rainfall, or changes to flora and fauna as a consequence of physical or climatic changes) could impact recruitment by altering food sources or preferred habitats.	

STATE OF KNOWLEDGE SUMMARY

Rock lobster (CRA), *Jasus edwardsii*, Kōura (*also called Spiny red rock lobster*)

Characteristic	Details	Reference
Fishery	Primarily a pot fishery around North and South Islands, Stewart Island, and Chatham Islands. There is a large recreational fishery and it was also an important customary food for Māori.	MPI 2015b
Habitat	Rocky shores and near-shore reefs.	
Distribution	Occur around the New Zealand mainland and its offshore islands (excluding Campbell Island). Long-distance migrations have been observed in some areas. During spring and early summer, small males and immature females move various distances against the current from the east and south coasts of South Island towards Fiordland and south Westland.	
Stock structure	No evidence for genetic subdivision of stocks within New Zealand from biochemical genetic and mtDNA studies. Observed long-distance migrations in some areas and long larval life probably result in genetic homogeneity among areas. Gene flow probably occurs to New Zealand from populations in Australia.	MPI 2015b
Depth range	Generally between depths of about 5 to 200 m.	
Temperature range	Adult rock lobster appear to be able to tolerate water temperatures over the range 4–20 °C, but their optimal preferred range is not known.	
Recruitment	Settlement indices measured on artificial collectors can fluctuate widely from year to year.	MPI 2015b
Reproduction	Mating takes place after moulting in autumn, and the eggs hatch in spring into the short-lived naupliosoma larvae. Most of the phyllosoma larval development takes place in oceanic waters tens to hundreds of kilometres offshore over at least 12 months. Near the edge of the continental shelf the final-stage phyllosoma metamorphoses into the settling stage, the puerulus. Puerulus settlement takes place mainly at depths less than 20 m, but not uniformly over time or area.	Booth et al. 2000; Chiswell & Booth 1999, 2005, 2007
Growth	Based on tag and recapture data, rock lobsters are thought to be relatively slow-growing and long-lived. Sexual maturity in females is reached from 34–77 mm tail width (TW), depending on locality within New Zealand. For instance, around Gisborne, 50% maturity appears to be realised near 40 mm TW while most females in the south and south-east of the South Island do not breed before reaching about 60 mm TW.	
Diet	Feeds primarily on molluscs and crustaceans, with smaller components of annelids, algae and echinoderms.	
Possible climate change challenges	Given their calcareous exoskeleton, rock lobster may be affected by ocean acidification. Under acidified conditions, early life stage *Homarus americanus* had shorter carapace length, slowed progress through larval moults, and reduced survival at the last stage, while *H. gammarus* exhibited reduction in carapace mass at the final stage. Conversely, a study of South African rock lobster *Jasus lalandii*, revealed no effects of ocean acidification on juveniles, and preliminary work on *J. edwardsii* did not reveal any significant impacts on juveniles over a 4 month experiment. Acidification may also influence their mollusc and echinoderm prey.	Chiswell & Booth 2007; Arnold et al. 2009; Keppel et al. 2012; Knapp et al. 2015

	Changes to ocean circulation patterns also have the potential to affect the recruitment of the rock lobster, given the extended phyllosoma stage.	

STATE OF KNOWLEDGE SUMMARY

Salmon, Chinook, *Oncorhynchus tshawytscha*

Characteristic	Details	Reference
Fishery	Primarily aquaculture in sheltered marine environments at Stewart Island, the Marlborough Sounds, and Akaroa Harbour. There are freshwater operations in Canterbury, Otago, and Nelson using ponds, raceways, and hydrocanals. New Zealand is the world's largest producer and market supplier of the Chinook salmon.	New Zealand Salmon Farmers Association 2011
Habitat	Farmed primarily in sea cages. 'Wild' fish appear to prefer braided river systems.	
Distribution	Introduced to New Zealand from California in the early 1900s, chinook salmon now occur mainly on the east coast of the South Island from the Waiau River in the north to the Clutha River in the south. The main runs occur in the large braided Canterbury rivers – the Waimakariri, Rakaia, Rangitata and Waitaki. Marine aquaculture of the species occurs at Stewart Island, the Marlborough Sounds, and Akaroa Harbour.	New Zealand Salmon Farmers Association 2011
Stock structure	Most chinook salmon in New Zealand waters will be descendants of ova introduced via a hatchery on the Hakataramea River, between 1901 and 1907. These were from the Baird Fish Station on the McLeod River a tributary of the Sacramento River in California, USA.	New Zealand Salmon Farmers Association 2011
Depth range	Sea-cage farming occurs in surface waters — the cages are seldom deeper than 25 m.	
Temperature range	Wild salmon in North America occur predominantly in waters from 4 to 19 °C, with the preferred range being 14 ± 3 °C.	Wurster et al. 2005
Recruitment	After hatching, the baby salmon are typically grown to smolt stage before they are transferred to the sea cages or ponds (at about age 8–13 months).	New Zealand Salmon Farmers Association 2011
Reproduction	Salmon are hatched in land-based hatcheries and transferred to sea cages or freshwater farms, where they are grown out to harvestable size of 3–4 kg. The broodstock for the farms is usually selected from existing farm stock or sometimes sourced from wild populations. Eggs and milt are stripped manually from sexually mature salmon and incubated under conditions (around 10–12 °C) replicating the streams and rivers where the salmon would spawn naturally.	New Zealand Salmon Farmers Association 2011
Growth	After introduction to the sea-cages, salmon take a further 18–30 months to grow to market size, i.e., about 3.5–4.0 kg.	New Zealand Salmon Farmers Association 2011
Diet	Wild Chinook salmon eat insects, amphipods, and other crustaceans while young, and primarily other fish when older. Farmed salmon are typically fed food pellets of fish meal specially formulated for Chinook salmon (typical proportions of the feed are: 45% protein, 22% fat, and 14% carbohydrate plus ash and water).	New Zealand Salmon Farmers Association 2011
Possible climate change challenges	Increases in sea surface temperature could negatively impact the growth rate of farmed salmon, and has been observed to increase mortality, particularly in the more northern operations.	

STATE OF KNOWLEDGE SUMMARY

Scampi (SCI), *Metanephrops challengeri*

Characteristic	Details	Reference
Fishery	Exclusively a trawl fishery using light bottom trawl gear. All vessels use multiple rigs of two or three nets of very low headline height. The main fisheries are in waters 300–500 m deep in the Bay of Plenty, Hawke Bay, Wairarapa Coast, Mernoo Bank, western Chatham Rise and Chatham Islands, and the Auckland Islands.	MPI 2015a
Habitat	Occur primarily on soft sediments. Scampi build a burrow in the sediment and may spend a considerable proportion of time within this burrow. There are daily and seasonal cycles of emergence from burrows onto the sediment surface. Catch rates are typically higher during the hours of daylight than night, and patterns vary seasonally between sexes and areas, dependent on the moult cycle.	MPI 2015a
Distribution	Widely distributed around the New Zealand coast, on the continental slope. Generally only present in commercial densities on the East coast.	MPI 2015a
Stock structure	Not well known. Preliminary electrophoretic analyses suggest that scampi on the Auckland Island shelf are genetically distinct from those in other areas. There is substantial genetic heterogeneity in samples from off eastern North Island and Chatham Islands. The abbreviated larval phase of this species may lead to low rates of gene mixing. Differences among some scampi populations in average size, size at maturity, the timing of diel and seasonal catchability cycles, and CPUE trends also suggest that multiple stocks are likely.	MPI 2015a
Depth range	Commercially fished mainly between depths of 300 and 500 m. About 95% of the research trawl catch occurred between 315 and 495 m, with the mean depth being 350 m.	MPI 2015a; Figure 8
Temperature range	Found in a relatively narrow temperature range (95% interval 7–12 °C) with a mean at 10.3 °C.	Figure 8
Recruitment	Recruitment appears to have varied over time, but there is no information on the drivers of this variability. Some stocks show very similar patterns to adjacent rock lobster populations, suggesting broad scale environmental drivers.	
Reproduction	Examination of ovary maturity suggests that 50% of females were mature at 30 mm carapace length off eastern North Island, and at about 38 mm at Auckland Islands. The peak of moulting and spawning activity seems to occur in spring or early summer. Larval development time is probably very short and may be less than three days in the wild. The abbreviated larval phase may, in part, explain the low fecundity of New Zealand scampi.	MPI 2015a
Growth	Relatively little is known of the growth rate of any *Metanephrops* species in the wild. Males grow to a larger size than females. The maximum age of New Zealand scampi is not known, although analysis of tag return data and aquarium trials suggest that this species may be quite slow growing and long lived, taking up to 6 years to recruit to the commercial fishery. Results from aquarium trials suggested that scampi are about 3–4 years old at 30 mm carapace length and may live for 15 years. Scampi moult several times per year in early life and probably about once a year after sexual maturity (at least in females).	MPI 2015a
Diet	Only limited information is available on the diet of *M. challenger*. Other nephrophids are known to feed on	Hine 1976

	small fishes and crustaceans, both live and scavenged.
Possible climate change challenges	No known challenges. Given their calcareous exoskeleton, scampi may be affected by ocean acidification. They are limited in their distribution by sediment type, and appear to prefer a relatively narrow temperature range, so changes in water temperatures could make some current stock areas unsuitable. Scampi are only available for capture when emerged from burrows. Temperature or acidification related changes to emergence patterns would have implications for fisheries.

STATE OF KNOWLEDGE SUMMARY

Shark, Blue (BWS), *Prionace glauca*, Mangō ripi

Characteristic	Details	Reference
Fishery	Taken by recreational, customary, and commercial long-line fishing method. Nearly all the commercial catch (98–99%) is taken by surface longliners targeting tunas and swordfish.	Francis 2013b; MPI 2016c
Habitat	A highly migratory, oceanic pelagic carcharhinid that is also often found over continental shelves, and occasionally comes close to shore. Blue sharks in the North Pacific are segregated by size and sex and migrate seasonally and latitudinally for mating and pupping. Different components of the population prefer different latitudinal bands. Similar migrations probably occur in the South Pacific around New Zealand.	Nakano 1994; MPI 2016c
Distribution	Found throughout the world's oceans in all tropical and temperate waters from about 50° N to 50° S. In New Zealand waters the longline fishing effort is distributed along the east coast of the North Island and the south west coast of the South Island where this species most commonly occurs. Blue shark abundance is greatest in northern North Island waters. Pregnant females are mainly found in the Kermadec and Auckland FMAs, indicating a preference for subtropical waters. Most blue sharks caught by surface long liners in New Zealand waters are immature.	Francis 2013b; MPI 2016c
Stock structure	Assumed to be part of the wider South Western Pacific Ocean stock.	
Depth range	Surface to over 1000 m, but usually in the upper 200 m of the water column.	Figure 8; MPI 2016c
Temperature range	Prefers waters with a temperature range of 7–16 °C but will tolerate temperatures of 21 °C or above.	
Recruitment	Blue sharks appear to be fully recruited to the commercial longline fishery by the end of their second year.	MPI 2016c
Reproduction	In New Zealand waters, male blue sharks are sexually mature at about 190–195 cm FL and females at about 170–190 cm FL. Gestation in female blue sharks lasts between 9–12 months and between 4–135 pups (averaging 26–56) are born alive, probably during the spring. Pups are probably born at about 50 cm FL. Pregnant females are mainly found in the Kermadec and Auckland FMAs.	Francis & Duffy 2005; MPI 2016c
Growth	Males and females appear to grow at similar rates until about seven years of age, when their growth appears to diverge. Age-at-maturity is estimated at 8 years for males and 7–9 years for females. The maximum recorded ages of males and females in New Zealand waters are 22 and 19 years, respectively.	Manning & Francis 2005; MPI 2016b
Diet	Feed opportunistically on a range of living and dead prey. Fish and squid dominate the diet, with the former increasing in importance in larger sharks.	Griggs et al. 2007; Horn et al. 2013
Possible climate change challenges	The highly migratory behaviour and latitude preferences by different size and sex components of the population suggest that the distribution of this species may be affected by temperature changes. Blue sharks are likely to extend further south in greater numbers, and remain around New Zealand for more of the year, as water temperature increases.	

STATE OF KNOWLEDGE SUMMARY

Shark, Dark Ghost (GSH), *Hydrolagus novaezealandiae*

Characteristic	**Details**	**Reference**
Fishery	Two species (dark and pale ghost sharks) make up commercial landings. Dark ghost sharks were introduced into the QMS from the beginning of the 1998–99 fishing year. Taken as a bycatch of other target trawl fisheries e.g., hoki, squid. Prior to becoming a QMS species often unknown quantities were discarded and not recorded. In addition, has been mis-reported as pale ghost shark. Ford et al. (2015) ranked dark ghost shark seventh highest in terms of risk of the eleven QMS chondrichthyan species.	MPI 2016a; Ford et al. 2015
Habitat	A benthic dwelling species. Trawl surveys show that dark and pale ghost shark exhibit niche differentiation, with water depth being the most influential factor, although there is some overlap of habitat. On the Chatham Rise, the main overlap range appears quite compact (from about 340 to 540 m). In the Southland/Subantarctic region, the overlap range is wider (about 350 to 770 m).	MPI 2016a
Distribution	Occur through much of the EEZ but sparse north of 40° S and have not been recorded from the Bounty Plateau. Most abundant on the west coast of the South Island and Chatham Rise, on the Stewart-Snares shelf and Southland/Subantarctic. Smaller sharks (<40 cm) are more abundant in waters shallower than 200 m.	MPI 2016a
Stock structure	Likely two main stocks based on difference in maximum size of dark ghost sharks: the eastern fishery, extending from the upper east coast of the South Island and out east across the Chatham Rise; the southern fishery, extending from the lower east coast of the South Island, south around the Stewart/Snares shelf, Campbell Plateau, and Puysegur trench.	MPI 2016a; Horn 1997
Depth range	30 to 850 m. Most abundant in 150–500 m on the west coast of the South Island and the Chatham Rise, and in depths of 150–700 m on the Stewart-Snares shelf and Southland/Subantarctic. Smaller sharks (<40 cm) are more abundant in waters shallower than 200 m, particularly in the Canterbury Bight.	MPI 2016a
Temperature range	Found in broad temperature range (95% interval 8.5–13°C) with a median at 9.6°C.	Figure 8
Recruitment	East coast South Island winter surveys have had a large component of pre-recruit biomass. Elasmobranchs are believed to have a strong stock-recruit relationship; the number of young born is related directly to the number of adult females. It is suggested this is not the case for this species.	Beentjes et al. 2015
Reproduction	Oviparous, young hatch from egg case at about 9–12 cm. Fecundity in New Zealand waters is unknown. Occasionally, large trawl catches (>300 kg tow^{-1}) have been recorded, suggesting this species may form aggregations for feeding, or perhaps reproduction (Horn 1997).	Cox & Francis, 1997; Horn 1997
Growth	No published information is available on the age of any *Hydrolagus* species. Francis & Ó Maolagáin (2001) found that growth rates were similar and moderately rapid for males and females, with both sexes reaching 50 cm in 5–9 years. Length-	Francis & Ó Maolagáin 2001

	frequency histograms indicate that females grow to a larger size than males. On the Chatham Rise, the estimated size at 50% sexual maturity for dark ghost sharks is 52–53 cm for males and 62–63 cm for females.	
Diet	Predominantly a benthic feeder, diet dominated by crabs and sea urchins.	Dunn et al. 2010b
Possible climate change challenges	Water temperature changes might affect the smaller ghost sharks that are abundant in shallower waters and the ECSI nursery grounds. Ocean acidification could impact the abundance of urchins, a main dietary component of dark ghost sharks.	

STATE OF KNOWLEDGE SUMMARY

Shark, School (SCH), *Galeorhinus galeus*, Tupere, Tope, Makohuarau

Characteristic	Details	Reference
Fishery	A setnet, bottom longline, and bottom trawl fishery. Caught from 1940s onwards. Landings rose steeply from the late 1970s until 1983 with the intensification of setnets targeting this and other shark species, and a general decline in availability of other, previously more desirable, coastal species. Early on, in the fishery, there was significant discarding and under-reporting. Landings have remained near the level of the TACC (3436 t) since 1995–96. Of the 88 individuals landed by longline in 2015, 43.5% were retained (estimated from Observer data Table 5. Pacific Bluefin assessment. November 2016). Listed as a gamefish and regularly caught by recreational fishers (commonly in set nets). Māori fishers made extensive use of school shark in pre-European times for food, oil, and skin. No information on the current level of customary non-commercial take. In some parts of the world this species has IUCN Red List Status of Vulnerable. Ford et al. (2015) ranked School shark 6th highest in terms of risk of the eleven QMS chondrichthyan species.	MPI 2016a; MPI 2016b; CITES 2013; Ford et al. 2015
Habitat	Mainly demersal on continental shelves, but also on the upper slopes, at depths from near shore to 550 m. Has been shown to be pelagic in the open ocean. Nursery grounds include harbours, shallow bays and sheltered coasts.	MPI 2016a; FishBase
Distribution	Found world-wide in temperate waters. Distributed across the New Zealand shelf, generally being inshore in summer and offshore in winter. The capture of school sharks by tuna long-liners shows that their distribution extends well offshore, up to 180 nautical miles off the South Island, and 400 nautical miles off northern New Zealand towards the Kermadec Islands. Tagged New Zealand school shark have been recorded from Australia.	MPI 2016a; Francis 2010
Stock structure	Probably a single biological stock in the New Zealand EEZ. Highly mobile, moving between the North and South Islands, and as far as Australia.	Francis 2010; MPI 2016a
Depth range	Surface to near the seafloor. Known to extend to depths of 1100 m.	FishBase; MPI 2016a
Temperature range	Because of its wide latitudinal and depth ranges, school shark experiences a wide temperature range.	
Recruitment	West coast South Island trawl surveys show several distinct juvenile year classes, but no analysis has been done to determine whether they provide a recruitment signal. In Australia, recruitment overfishing has occurred to such an extent that the stock is considered seriously threatened and a series of conservative management measures (TAC reductions) have been progressively imposed between 1996 and 2007 (Wilson et al. 2008). The most important conclusion from this for New Zealand is that fishing pressure on large mature females should be managed appropriately to maintain the productivity of this species.	MPI 2016a; Wilson et al. 2008; Francis & Mulligan 1988

Reproduction	Breeding assumed to be biennial but work on a Brazilian stock suggests that females have a 3-year cycle in the South Atlantic. Mating is believed to occur in deep water, probably in winter. Release of pups occurs during spring and early summer (November–January), apparently earlier in the north of the country than in the south. Nursery grounds include harbours, shallow bays and sheltered coasts through much of mainland New Zealand. The pups remain in the shallow nursery grounds during their first one or two years and subsequently disperse across the shelf. Pregnant females with embryos at a range of developmental stages (but not full-term) are known to aggregate in a few places, notably Kaipara Harbour, but there are other unknown locations.	Peres & Vooren 1991; MPI 2016a
Growth	School sharks are slow growing and long-lived. Growth is fastest for the first few years, slows appreciably between 5 and 15 years, and is negligible at older ages, particularly after 20. Results from an Australian long-term tag recovery programme suggest a maximum age of at least 50 years. Age-at-maturity has been estimated at 12–17 years for males and 13 to 15 years for females (Francis & Mulligan 1998).	Peres & Vooren 1991; Francis & Mulligan 1998.
Possible climate change challenges	Increased water temperatures may increase growth rates, but its effect on recruitment cannot be predicted. An increase in water temperature might displace the pupping and nursery grounds southwards. School sharks are tolerant of a wide range of temperatures, but their distribution may shift southwards as coastal temperatures increase.	

STATE OF KNOWLEDGE SUMMARY

Silver warehou (SWA), *Seriolella punctata*, Warehou

Characteristic	Details	Reference
Fishery	Taken almost exclusively by trawl (bottom and midwater), mainly as a bycatch of the hoki, squid, barracouta and jack mackerel fisheries.	MPI 2015a
Habitat	A schooling bentho-pelagic species.	
Distribution	Occurs across most of the New Zealand continental shelf, but most abundantly around South Island, southern North Island, and along Chatham Rise. Juvenile fish inhabit shallow water at depths of 150–200 m and remain apart from sexually mature fish. Juveniles have been caught in Tasman Bay, on the east coast of the South Island and around the Chatham Islands. Once sexually mature, fish move out to deeper water along the shelf edge.	Anderson et al. 1998
Stock structure	The stock structure is unknown. It is uncertain whether the same stock migrates from one area to another, spawning whenever conditions are appropriate, or if there are several separate stocks.	Horn et al. 2011; MPI 2015a
Depth range	Found from about 30 to 700 m. Most of the commercial catch was taken in depths from 200 to 600 m deep. About 95% of the research trawl catch occurred between 100 and 500 m, with the mean depth being 280 m.	Hurst et al. 2000; Anderson et al. 1998; Figure 8
Temperature range	Research trawls have captured silver warehou in a relatively narrow temperature range (95% interval 7–12 °C) with a mean at 10.3 °C.	Figure 8
Recruitment	Length-frequency distributions from trawl survey series are extremely variable among years. The variability is highest in the East Coast South Island survey, which shows up to four distinct size modes, but usually only one or two simultaneously. This variability in the size classes captured could be a result of environmental influences on either recruitment strength or fish distribution, or a consequence of fish schooling by size and the whole population not being sampled by the survey.	MPI 2015a
Reproduction	Spawning has been recorded at several grounds; on the western Chatham Rise, east coast North Island, west coast South Island, and the Stewart-Snares shelf in late winter, and at the Chatham Islands in late spring-early summer.	
Growth	Initial growth is rapid and fish reach sexual maturity at around 45 cm FL in 4 years. Maximum age is about 23 years for females and 19 years for males.	Horn & Sutton 1996
Diet	Almost exclusively a salp eater (97% of diet), but with minor components of pelagic crustaceans (mainly amphipods).	Horn et al. 2011; Stevens et al. 2011
Possible climate change challenges	Consumes a very narrow diet, so would be positively affected by an increase in salp abundance (salps are anticipated to replace krill in the food chain in some oceans in a high CO_2 world).	

STATE OF KNOWLEDGE SUMMARY

Snapper (SNA), *Chrysophrys auratus*, Tāmure, Kaorea

Characteristic	Details	Reference
Fishery	The predominant fishing method varies by stock. In some areas inshore trawling is the most productive snapper fishery. In other areas trawling, Danish seine and bottom longline all make significant contributions to commercial catch. Recreational and customary fisheries are also highly important, contributing up to 40% of the total allowable catch in some areas.	MPI 2015a
Habitat	An inshore demersal (epi-benthic) species occupying a wide range of habitats, including rocky and biogenic reefs, and areas of sand and mud bottom.	Parsons et al. 2014; Morrison et al. 2014b
Distribution	Abundant around northern North Island in waters shallower than 250 m, and only rarely present south of 42° S. After spawning (spring–summer) the fish often disperse to inshore feeding grounds. The winter grounds are thought to be in deeper waters where the fish are more widespread. Other fish are resident and do not move more than a few hundred metres. Juvenile snapper (0+ age class) are common in shallow harbours and estuaries around northern North Island, often associated with seagrass beds.	Anderson et al. 1998; Parsons et al. 2014
Stock structure	Snapper are thought to comprise either seven or eight biological stocks. These stocks comprise three in SNA 1 (East Northland, Hauraki Gulf and Bay of Plenty), two in SNA 2 (one of which may be associated with the Bay of Plenty stock), two in SNA 7 (Marlborough Sounds and Tasman/Golden bays), and one in SNA 8. Tagging studies reveal that limited mixing occurs between some of these stocks.	Parsons et al. 2014; MPI 2015a
Depth range	Found from the shoreline to 250 m. Most commercial fishery catches are in depths of 20–150 m, and 95% of the research trawl catch by weight occurred between 10 and 130 m, with the median depth being 25 m.	Hurst et al. 2000; Anderson et al. 1998; Figure 8
Temperature range	Found in a broad temperature range (95% interval 12–21 °C) with a median at 15.9 °C.	Figure 8
Recruitment	Autumn sea surface temperature (SST) appears to play an important part in the success of recruitment, at least around northern North Island. Generally strong year classes in the population correspond to warm years (~20 °C), weak year classes correspond to cold years (~18 °C).	Francis 1993; Dunn et al. 2009a
Reproduction	All snapper undergo a female phase as juveniles, but after maturity each individual functions as one sex (either male or female) for the rest of its life. Sexual maturity occurs at an age of 3–4 years. Snapper are serial spawners, releasing many batches of eggs during spring and summer. The larvae have a relatively short planktonic phase which results in the spawning grounds corresponding fairly closely with the nursery grounds of young snapper. The duration of the larval period is 18–32 days and is longer for snapper spawned early in the spawning season, when water temperatures are low, than for snapper spawned later in the season when temperatures are higher. Metamorphosis is probably size- rather than age-dependent. Back-calculated spawning dates ranged from September to March and peaked in November–January. Maximum spawning season duration was five months. Spawning onset was earlier when spring water temperature was higher than normal, and first spawning occurred at	Francis 1993, 1994a, b; Parsons et al. 2014

	14.8–15.6 °C, indicating that spawning onset is temperature-dependent. Large schools of snapper congregate before spawning and then move on to the spawning grounds.	
Growth	Growth rate varies geographically, seasonally, and from year to year. Snapper from the northern South Island and the west coast of the North Island grow faster and reach a larger average size than elsewhere. Snapper have a strong seasonal growth pattern, with rapid growth from November to May, and then a slowing down or cessation of growth from June to September. They may live up to 60 years or more.	Francis 1994a; MPI 2015a
Diet	Consumes a very broad range of benthic and epi-benthic invertebrates (i.e., primarily crustaceans, but also molluscs, polychaetes, echinoderms, tunicates). Fish is a minor dietary component. Marked ontogenetic changes in diet are apparent; juveniles (< 10 cm length) concentrate on small epi-pelagic and benthic crustaceans (primarily copepods), with larger crustaceans (e.g., crabs) and bivalves becoming more important for larger fish.	Stevens et al. 2011; Usmar 2012; Parsons et al. 2014
Possible climate change challenges	Water temperature is an important driver of growth, spawning and recruitment success. International studies and New Zealand experimental work indicate that growth response to temperature is generally positive (Martino et al. 2019; McMahon et al. 2020; Parsons et al. 2020), but thermal maxima and how these vary spatially around New Zealand are unknown (D. Parsons, NIWA, pers. comm.). Shallow estuaries are a key habitat for juvenile snapper. Recruitment to the northern stocks may be largely dependent on nurseries in a small number of estuaries; modifications to these (e.g. increased sedimentation, changes to flora and fauna) could impact recruitment.	

STATE OF KNOWLEDGE SUMMARY

Southern blue whiting (SBW), *Micromesistius australis*

Characteristic	Details	Reference
Fishery	Exclusively a trawl fishery, primarily using midwater nets.	MPI 2015a
Habitat	A bentho-pelagic offshore species.	
Distribution	Almost entirely restricted to Subantarctic waters. They are dispersed throughout the Campbell Plateau and Bounty Plateau for much of the year, but during August and September they aggregate to spawn near the Campbell Islands, on Pukaki Rise, on Bounty Plateau, and near the Auckland Islands over depths of 250–600 m.	Anderson et al. 1998
Stock structure	There appear to be four main spawning grounds of southern blue whiting; on the Bounty Plateau, Pukaki Rise, Auckland Islands shelf, and Campbell Island Rise. There are also consistent differences between these four areas in the size and age distributions of fish, in the recruitment strength, and in the timing of spawning.	Hanchet 1999
Depth range	Found from about 200 to 700 m. The commercial catch is taken mainly between 350 and 600 m. About 95% of the research trawl catch occurred between 210 and 540 m, with the mean depth being 470 m.	Hurst et al. 2000; Anderson et al. 1998; Figure 8
Temperature range	Found in a very narrow temperature range (95% interval 6–7°C) with a mean at 7.0 °C.	Figure 8
Recruitment	This species is characterised by highly variable year class strengths, with the strong year classes growing at a significantly lower rate than others. It appears that better recruitment arises from rough winters with a high degree of mixing, followed by relatively calm spring conditions.	Hanchet & Renwick 1999; Willis et al. 2007
Reproduction	Southern blue whiting are highly synchronised batch spawners. Four spawning areas have been identified: on Bounty Plateau, Pukaki Rise, Auckland Islands Shelf, and Campbell Island Rise. The Campbell Island Rise has two separate spawning grounds, to the north and south respectively. Spawning on Bounty Plateau begins in mid-August and finishes by mid-September. Spawning begins 3–4 weeks later in the other areas, finishing in late September/early October. Most fish mature to spawn at 3–4 years.	
Growth	Fish reach a length of about 20 cm FL after one year and 30 cm FL after two years. Growth slows down after five years and virtually ceases after ten years. Growth is density dependent. Maximum age is perhaps 25 years.	Hanchet & Uozumi 1996
Diet	Crustaceans comprise about two-thirds of the southern blue whiting diet, mainly euphausiids, but also natant decapods and amphipods. Teleosts comprise about one-third, and most of those were mesopelagics, mainly myctophids. Salps and cephalopods were of less importance.	Stevens et al. 2011
Possible climate change challenges	Successful recruitment appears to be strongly related to climatic variables. The species also has a very narrow preferred temperature range, so small temperature changes could be influential. Krill (euphausiids), a major prey species, are potentially impacted by ocean acidification (as they are in Antarctica; Kawaguchi et al. 2013).	

STATE OF KNOWLEDGE SUMMARY

Tarakihi (TAR), *Nemadactylus macropterus*

Characteristic	Details	Reference
Fishery	Mainly an inshore trawl fishery. Most of the catch around North Island is targeted, whereas South Island catches are more often by-catch (generally in target barracouta and red cod bottom trawl fisheries). There is a small target tarakihi setnet fishery off Kaikoura.	MPI 2015a
Habitat	A demersal (epi-benthic) species, generally inshore, sometimes associated with biogenic habitat.	Morrison et al. 2014a, b
Distribution	Occurs around the entire New Zealand mainland coastal shelf, on the western Chatham Rise, and at the Chatham Islands.	Anderson et al. 1998
Stock structure	Chatham Islands fish are believed to comprise a distinct stock. For eastern mainland fish, the current stock hypothesis is that the Canterbury Bight /Pegasus Bay area represents the main nursery area for the eastern stock unit. At the onset of maturity, a proportion of the fish migrate northwards to recruit to the East Cape area and, subsequently, the Bay of Plenty and east Northland areas. This hypothesis is further supported by the northward movement of tagged fish from the Kaikoura coast to the Wairarapa, East Cape and Bay of Plenty areas. Western mainland tarakihi stock structure is uncertain; a more comprehensive analysis of the available data sets is required to further investigate the stock structure between tarakihi in TAR 7 and the east coast areas, especially around the South Island.	Fisheries New Zealand 2018
Depth range	Found from the shoreline to 500 m. Most commercial fishery catches are in depths of 100–200 m, and 95% of the research trawl catch occurred between 40 and 300 m, with the mean depth being 120 m.	Hurst et al. 2000; Anderson et al. 1998; Figure 8
Temperature range	Found in a relatively broad temperature range (95% interval 8–15 °C) with a mean at 11.8 °C.	Figure 8
Recruitment	No estimates of recruitment strength are available for tarakihi. A significant positive correlation between estimated tarakihi abundance off east coast North Island and SST has been noted.	Dunn et al. 2009a
Reproduction	Tarakihi spawn in summer and autumn in several areas around New Zealand. The three main spawning grounds identified are Cape Runaway to East Cape, Cape Campbell to Pegasus Bay, and the west coast of the South Island near Jackson Bay. They have a long pelagic larval phase of 7–12 months, so larvae can be widely dispersed.	
Growth	Tarakihi reach a maximum age of 40+ years. Initial growth is relatively rapid, but it slows at an age of 4–6 years (at 25–35 cm FL) when sexual maturity is reached.	
Diet	Consumes a very broad range of benthic invertebrates (i.e., crustaceans, molluscs, polychaetes, echinoderms). Fish is a negligible dietary component.	Stevens et al. 2011
Possible climate change challenges	Abundance may be positively correlated with temperature, so small increases in temperature may positively impact the more southern tarakihi stocks. Increasing ocean acidification could negatively impact the mollusc and echinoderm prey of tarakihi.	

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APPENDIX 2: Estimating fish distribution under climate change — preliminary investigation of the use of a statistical spatial population model

Summary

- We used a statistical spatially-explicit population model for the New Zealand region to estimate the environmental preferences for albacore tuna, and to predict their relative spatial distribution (areas of relatively high and low abundance).

- The model parameters were estimated using remote-sensed environmental data (sea surface temperature, net primary productivity) and fish abundance as inferred from commercial fishery catch rates.

- The model estimated that albacore had a preference for waters with a sea surface temperature greater than 16 °C, and net primary productivity greater than 573 mg C/m^2/d. The estimated temperature preference was consistent with previous studies.

- There have been two main fishery areas; the model explained the distribution of the relatively large fishery to the northeast of New Zealand quite well but explained the fishery to the southwest of New Zealand less well. The model correctly (to the best of our knowledge) predicted the absence of albacore from most New Zealand waters during the winter and spring, and the absence of albacore from Chatham Rise.

- Under climate change scenarios, the model predicted that the available habitat for albacore in New Zealand waters would become much more extensive and would shift about two degrees further south. The model predicted that albacore would become available for capture around northern New Zealand throughout the year and would have a preference for Chatham Rise during the autumn.

- The statistical estimation of parameters for spatially and temporally explicit models requires good and numerous data. Poor model convergence was encountered, and multiple model runs were required to achieve best parameter estimates. The Spatial Population Model software used here was useful in simulating and understanding fish distribution, but additional, more relevant, good quality, and consistent data would improve the veracity of future research efforts. The present study was preliminary, but we believe results and insight from this approach could be improved.

- The most intensive tasks were data compilation and grooming. Once data were collated and compiled, the actual model runs were relatively straightforward.

Introduction

Spatial heterogeneity can arise in fish populations because of many factors, including biological variation (Begg et al.1999), environmental variability (Lande et al. 1999; Lovett et al. 2005; Williams et al. 2002), habitat availability (Botsford et al. 2009; Spencer 2008), or spatially variable exploitation (Booth 2000; Prince & Hilborn 1998; Stelzenmuller et al. 2008).

Here we used a statistical population model that uses environmental variables to predict the relative distribution of South Pacific albacore (*Thunnus alalunga*), a highly migratory species around New Zealand. The model estimates the relationship between environment ("preference layers") and population dynamics (in this study spatial distribution) from historical data, and then predicts the relative spatial distribution of the population under future climate scenarios.

The spatial population model used in this investigation is the Spatial Population Model (SPM) software (Dunn et al. 2016), a modification of the stock assessment package CASAL (Bull et al. 2012). SPM applies a generalised spatially explicit demographic model to estimate relative distribution of fish by area, as per demographic characteristics and movement preferences. The spatial movement idea in SPM is that populations are distributed based on preferred attributes for their environment. These attributes can include any biotic and abiotic factor in the environment that affects the population's spatial distribution. The model estimates these preferences from historical data on the environmental attribute, and distribution of fish. In this case, information on the environment comes primarily from remote sensed data, and information on the fish distribution from commercial fishery catch rates.

Highly migratory species (HMS) such as tuna are ideal species on which to test a spatial model. Typically, HMS populations vary substantially through space and time, and migrations have already been linked to environmental conditions and habitat (Clemens 1961; Nakamura 1969). Here we model the South Pacific albacore caught around New Zealand by the longline and trolling fishing fleets. It is thought that there is single stock of albacore in the South Pacific (Murray 1994). The stock is thought to be confined to an area with borders going from the equator to 50° S and from 140° E to 80° W. However, we only model the species when it enters the waters around New Zealand (EEZ).

Previous studies have shown correlations between sea surface temperature, and albacore presence and absence (Horn et al. 2013), and relative abundance measured from catch rates (Lee et al. 2005). The environmental attributes used here were sea surface temperature, net primary productivity, depth, and distance between areas. The latter is used to control the extent of movement from one time step to another, and, if selected by the model, will restrict the spatial movement between time steps to a plausible level. These environmental attributes were included because: they had previously been shown to influence fish distribution, we wanted to keep the model relatively simple for this preliminary investigation (no more than two or three estimated environmental effects), and they were readily available from the global coupled climate models used for forecasting.

Methods

1. SPM

Spatial Population Model (SPM) is a program for modeling population dynamics and spatial distribution of a fish stock (Dunn et al. 2016). The population model implemented in SPM is a spatially explicit age based demographic population model. At its core, SPM is a conventional age based demographic model (Haddon 2010) that keeps track of numbers of fish in specific age classes over time. Like all demographic models, SPM can apply population processes such as recruitment, growth, maturation, and mortality. SPM then has an additional array of spatial population movement processes that the user can implement. The "movement processes" (of fish from one area to another) used in this study were based on the concept of preference, where the population is distributed over an area based on a known (observed) distribution of spatially and temporally varying characteristics, and where highly preferable areas contain a higher proportion of the population compared to less preferable areas.

Process Model

The SPM process model that was applied was as follows,

$$N_{t,k} = f(N_{t-1,K}, \boldsymbol{X}_{t,k}; \boldsymbol{\theta}, \boldsymbol{\phi})$$

Where $N_{t,k}$ is abundance in cell *k* at time step *t*, $\boldsymbol{X}_{t,k}$ is the vector of environmental attributes for cell *k* in time step *t*. $f(N_{t-1,K}, \boldsymbol{X}_{t,k}; \boldsymbol{\theta}, \boldsymbol{\phi})$ is the preference function controlled by $\boldsymbol{\phi}$, and population processes controlled by $\boldsymbol{\theta}$. $N_{t-1,K}$ is the abundance in all cells that contribute abundance to cell *k* from the previous time step.

The time steps in the model were set to be seasonal (3 month groups), and the spatial resolution was set as 1° latitude and longitude cells. The spatial resolution was determined by the available resolution of environmental attributes, whereas the temporal resolution was chosen as a compromise between computational efficiency and capturing changing temporal conditions.

Observation model

The fisheries catch and effort data available to inform the model were data collected by Ministry for Primary Industries (MPI) observers on surface longline vessels and stored in the centralised observer database (*cod*), administered by NIWA for MPI. All records between 25 March 1994 and 28 August 2012 (a period for which corresponding environmental data were available) for surface longline were extracted from *cod*. The catch recorded was number of individual fish caught per fishing event, and included all seasons, and both zero and positive catch records. Each fishing event was allocated to a cell defined by the start latitude, longitude, season, and year. The measurement of effort was the number of hooks present on the longline. The relative abundance index, CPUE, was catch was divided by number of hooks. The relationship between estimated abundance $N_{t,k}$ and CPUE $I_{t,k}$ is expected to be proportional, given by,

$$I_{t,k} = qN_{t,k}e^{\varepsilon_{t,k}}$$

where $N_{t,k}$ is abundance in cell k at time step t, $I_{t,k}$ is the CPUE, q is the catchability coefficient, and $\varepsilon_{t,k}$ is the observational error. CPUE was not standardized for this investigation.

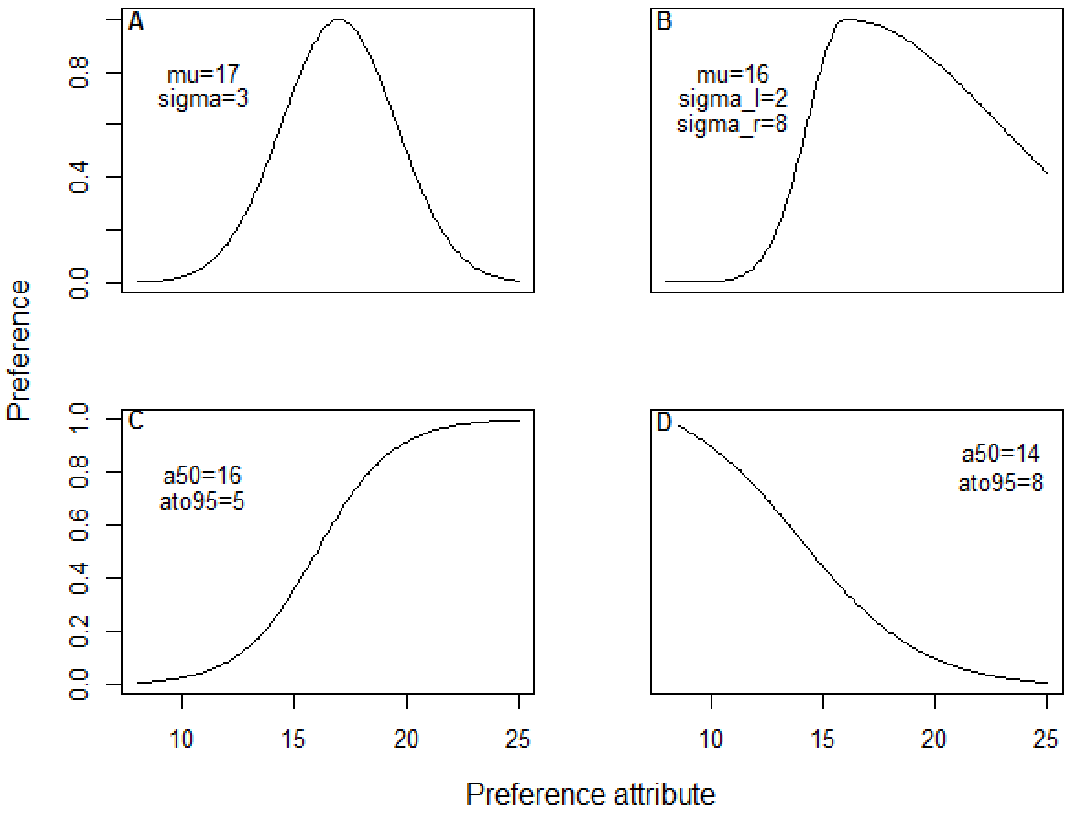
Preference Functions

The use of preference functions is central to SPM. The preference function describes the relative preference of the fish biomass for a given location and time, based upon the conditions encountered there. By comparing the observed environmental conditions ("layers") with the observed CPUE, the model is able to statistically estimate the parameters of the preference function.

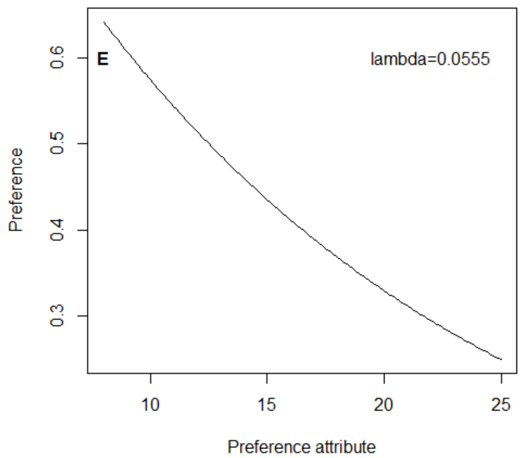
Suppose there exists an attribute **X**, and that its values $x_k$are known for all cells of the model for all time steps. With an assumed preference, functional form$f(x_k, \boldsymbol{\phi})$, SPM can estimate the preference value p_k for each cell k. SPM can also incorporate multiple attributes $X_1, X_2, X_3 \dots X_n$ calculating the joint preference value p_k of preference for cell k (Dunn et al. 2016),

$$p_k = f_1(x_{1,k}, \boldsymbol{\phi}_1)^{\alpha_1} \times f_2(x_{2,k}, \boldsymbol{\phi}_2)^{\alpha_2} \times \dots \times f_n(x_{n,k}, \boldsymbol{\phi}_n)^{\alpha_n}$$

Where $\alpha_i$is a weighting factor for a preference function i. The preference functional forms available in SPM are shown in Appendix 2 Figures 1 and 2.



Appendix 2 Figure 1: Demonstrating functional shape of preference functions in Spatial Population Model (SPM), A = Normal, B = Double Normal, C = Logistic, D = Inverse Logistic.



Appendix 2 Figure 2: Exponential preference function plotted against an example environmental preference attribute, with parameters Lambda = 0.0555.

Model Selection

Model selection involved finding the ’best’ combination of preference attributes, preference functional forms, and optimal values for the parameters. The ’best’ model was defined as the most informative model, whilst considering parsimony, given the information available.

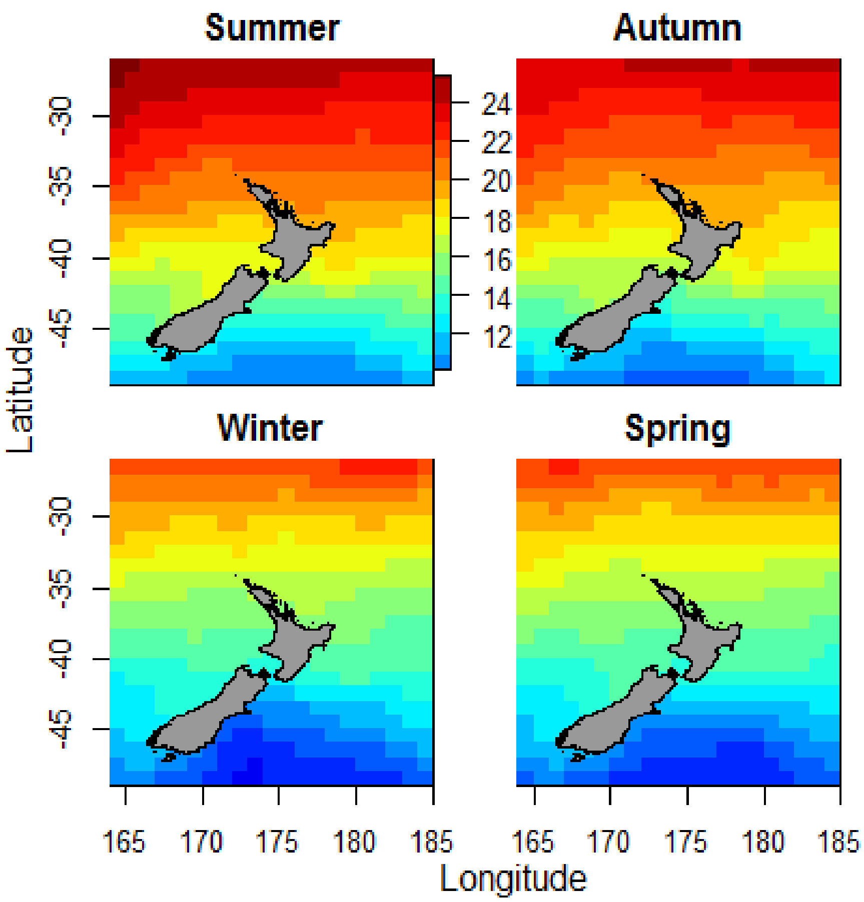
To find the ’best’ preference model a forward selection procedure was conducted. Competing model runs (i.e., model runs assuming different preference layers) were compared using Akaike Information Criterion (AIC), summarised residual fit, and parameter estimates.

2. Environmental Attributes

The environmental attributes investigated for selection by the model were sea surface temperature, net primary productivity, depth, and distance between areas.

Sea Surface Temperature (SST)

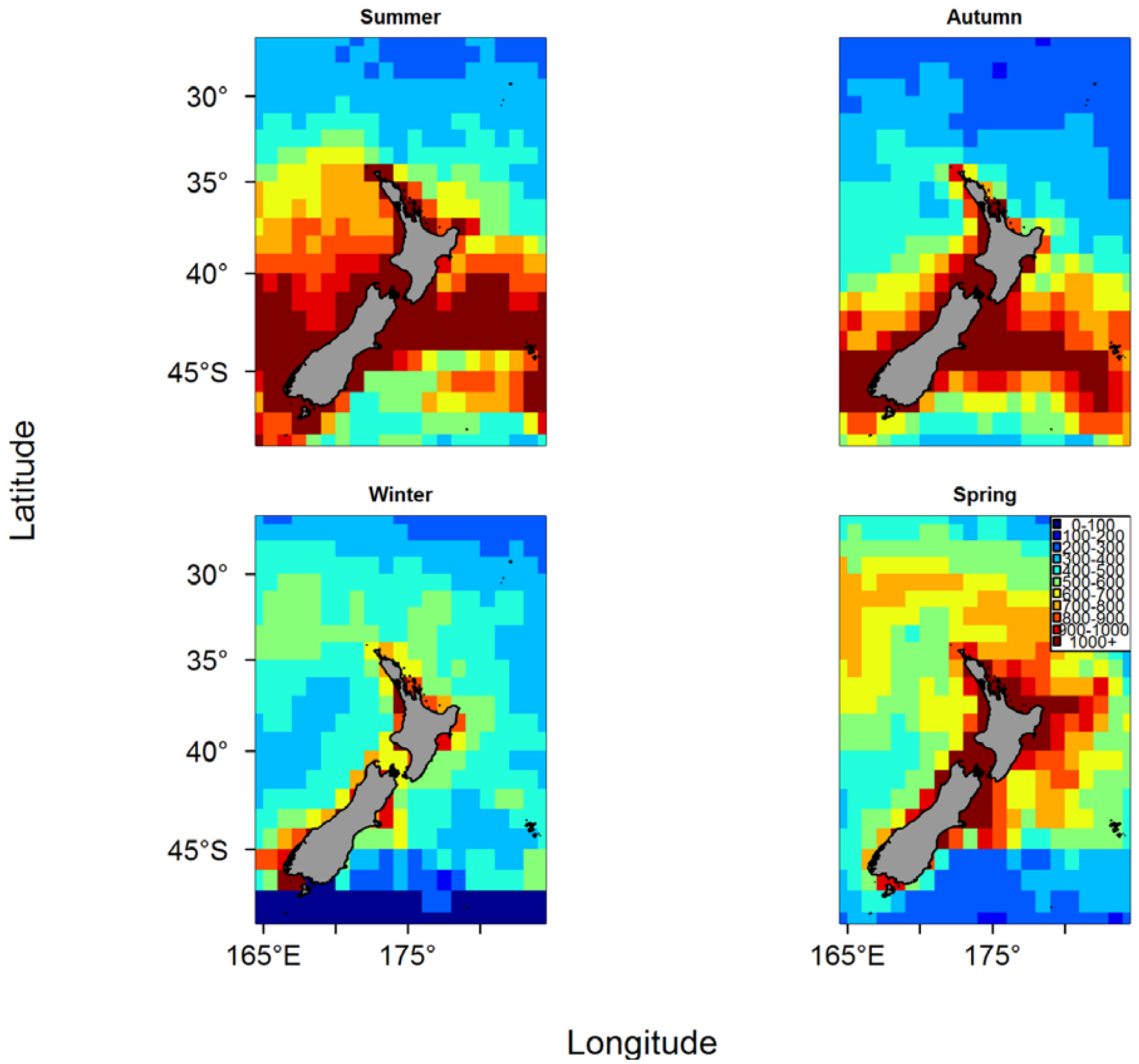
SST was the mean global skin (top 20 µm of the surface water) temperature of the ocean measured in °C. In this study, it was assumed that a change in temperature of the skin represented an equivalent change in temperature of at least the fished water column. The SST values were sourced from model NOAA OI.v2 SST (Reynolds & Smith 1994; Smith & Reynolds 1998). The temporal and spatial resolution was in monthly time intervals, on a 1° latitude and longitude spatial resolution (Appendix 2 Figure 3). The seasonal SST values for each cell were created by taking the mean of the respective monthly values for each season and location for each cell.



Appendix 2 Figure 3: Example of Sea Surface Temperature (SST) layer data by season used to predict the spatial distribution of albacore (example year 2010).

Net Primary Productivity (NPP)

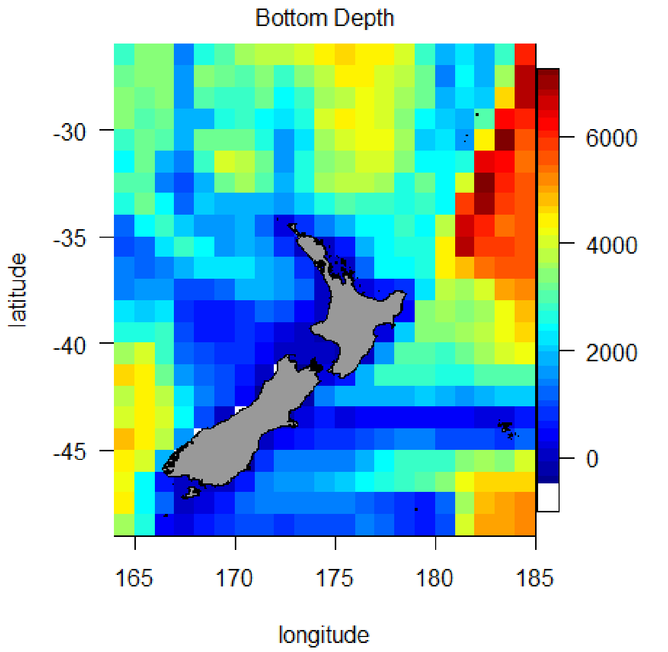
NPP was the average rate of net primary productivity, the amount of carbon per square metre per day ($mg\ C\ /m^2/d$). This attribute represented the ocean's carbon productivity, and thus can be assumed to be related to potential carbon available that an ecosystem can utilize for all other metabolic processes (Falkowski et al. 2003). NPP was sourced from the Oregon States Ocean Productivity website. NPP was derived via the Vertically Generalized Production Model (VGPM) (Behrenfeld & Falkowski 1997). There were two-time series (1997-2009 and 2002-2014). Each time series related to a different satellite sensor (SeaWiFS and MODIS-Aqua respectively). In this study the latter time series was used (MODIS, 2002-2014) (Appendix 2 Figure 4). Recent work has shown you can join the two time series (Pinkerton et al. 2016), and a longer time series might therefore be created for any future analyses. Further analyses would also update the time series to the present day (analyses here used a dataset from Craig Marsh's MSc thesis that were already processed and formatted for these analyses).



Appendix 2 Figure 4: Example of Net Primary Productivity (NPP) layer data by season used to distribute fish based on an estimated preference function (example year 2009). The units represent the seasonal average of net primary production measured as carbon fixed per square metre per day (mg C m^{-2} d^{-1}).

Depth

Bottom depth was the average depth from the ocean floor to a reference ellipsoid. Depth had been considered as a predictor for the distribution of other tuna species (Schick et al. 2004), although depth may well be aliasing for other factors (perhaps continental influence, mixing zones, etc.). Depth was sourced from https://koordinates.com/layer/1541-new-zealand-region-bathymetry/. The resolution of this product was in 250 m^2 cells. Bathymetry was assumed to be constant through time. For this study, we used the mean bathymetry over 1° latitude and longitude bins (Appendix 2 Figure 5).



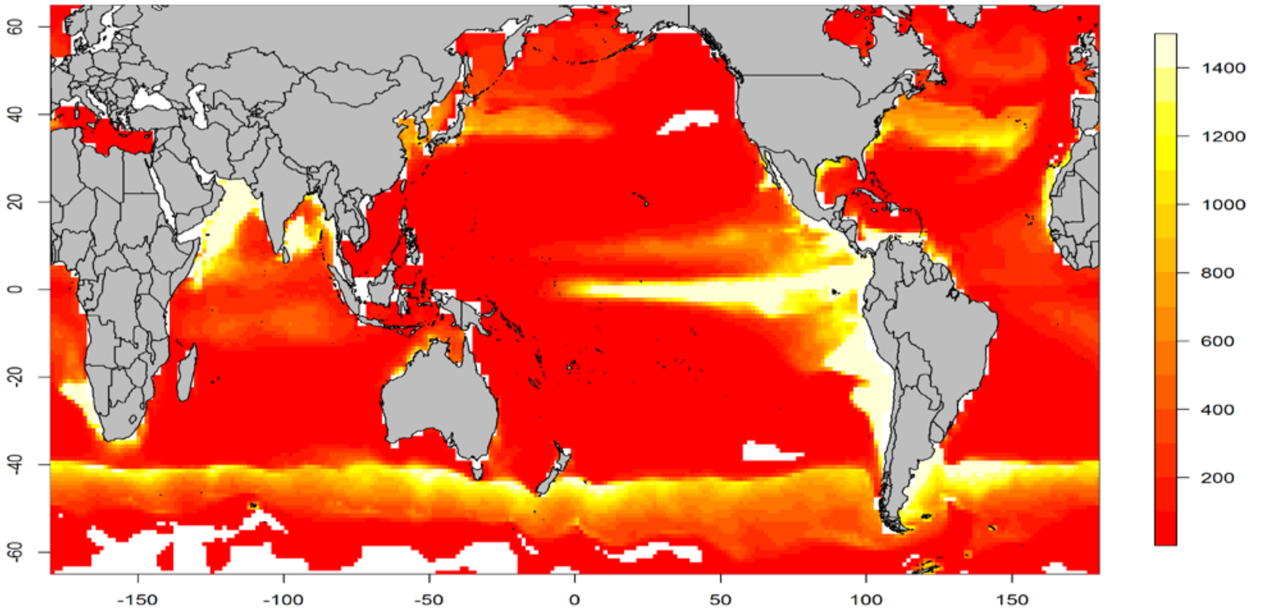
Appendix 2 Figure 5: Bathymetry for the New Zealand region, averaged into 1° latitude and longitude bins.

Distance

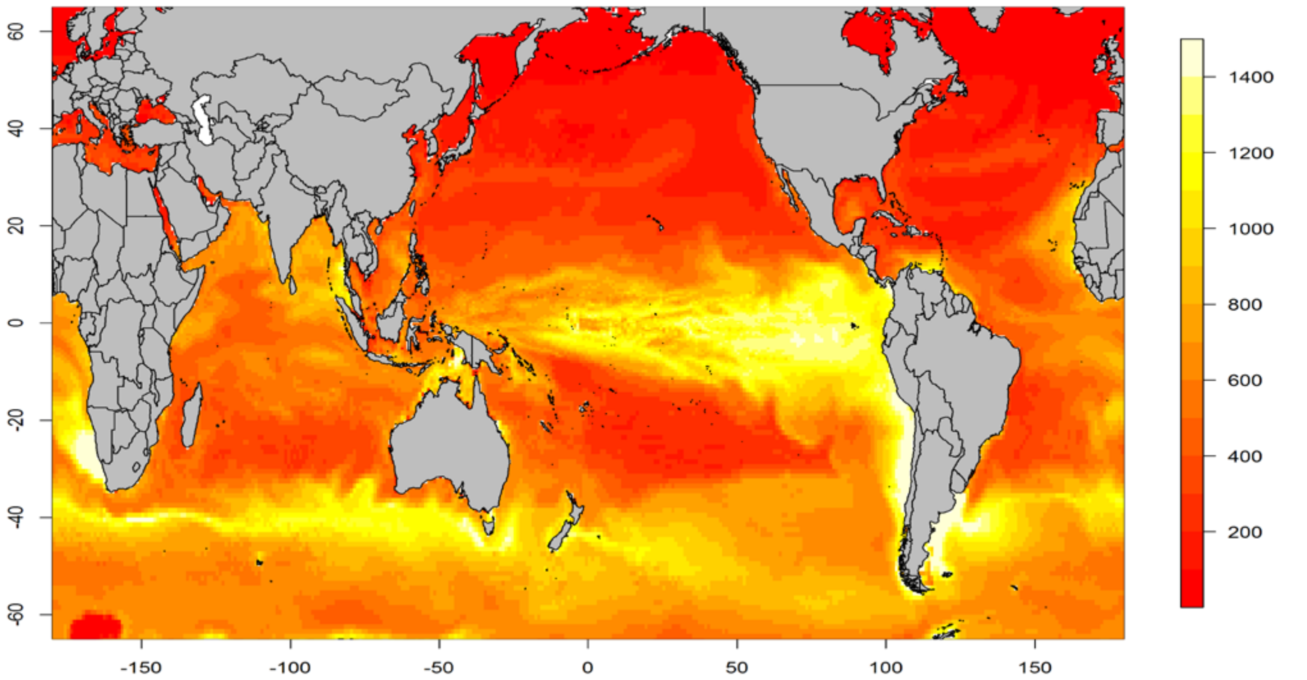
Distance was included for simple biological realism: suppose there are cells with equally preferable environmental conditions, but one is 100 km away and another is 1000 km away, then there should be a higher preference for cells that are closer, because less energy would be used for the same benefit. Distance was calculated within SPM using Dijkstra's shortest path algorithm, allowing for navigation around the islands of New Zealand, and changing cell size with latitude.

3. Climate change scenarios

Two global coupled models were considered for projecting environmental attributes into the future (G. Rickard, NIWA, pers.comm.); these were the second-generation Canadian earth system model (CanESM2) (Arora et al. 2011) and the global coupled carbon–climate Earth System Model (ESM2G) (Dunne et al. 2012). There were a range of scenarios available for projecting environmental attributes based on representative concentration pathways (RCPs) of greenhouse gases (GHGs) and aerosols. We chose the most extreme RCP of 8.5 to see how the spatial distribution was expected to change under the most extreme scenario available. SST global distribution was similar between the two models, but as shown in Appendix 2 Figures 6 and 7, the NPP distributions appeared to be quite different. We were unsure which model to choose, so arbitrarily chose ESM2G on the basis of it being at a spatial resolution that directly mapped to the chosen SPM resolution. The environmental attributes were predicted for two years, 2055 and 2100.



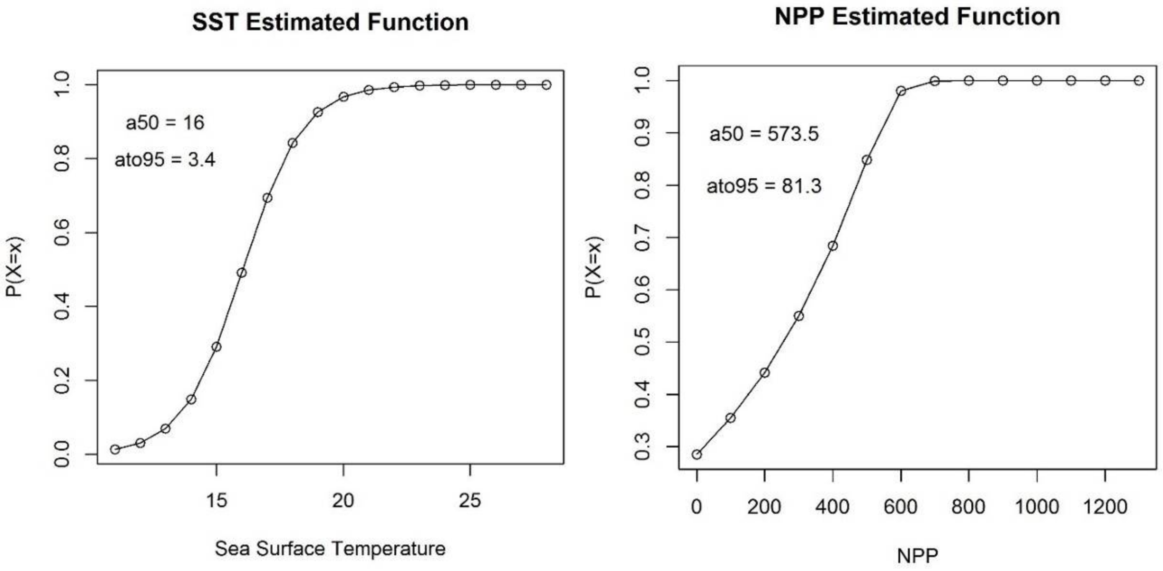
Appendix 2 Figure 6: Net Primary Productivity NPP (mg C m^{-2} d^{-1}) projected from the second-generation Canadian earth system model (CanESM2); example month presented is January 2036.



Appendix 2 Figure 7: Net Primary Productivity (NPP) (mg C m^{-2} d^{-1}) projected from the global coupled carbon–climate Earth System Model (ESM2G); example month presented is for January 2036.

Results

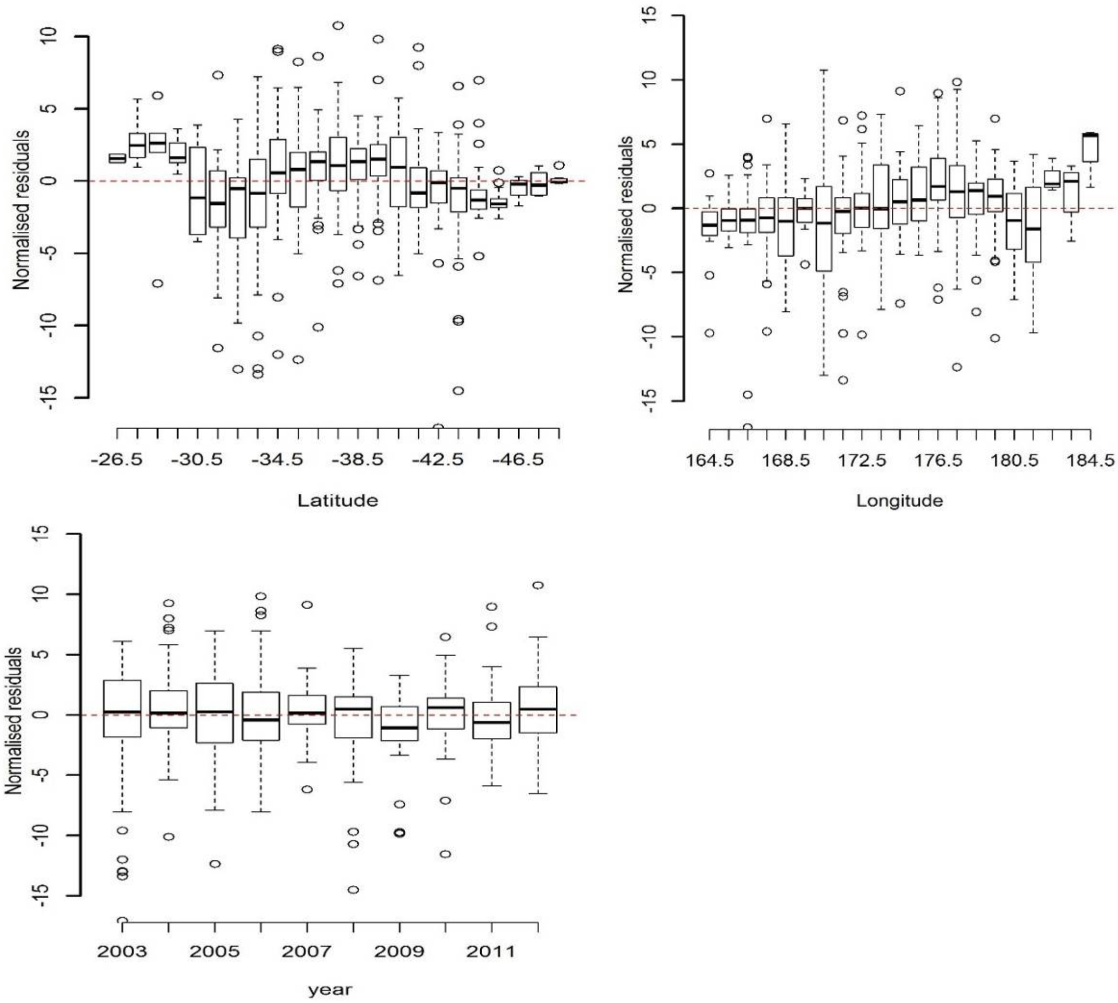
The best model using forward stepwise selection, contained Sea Surface Temperature (SST) and Net Primary Productivity (NPP) attributes. Both environmental attributes were best fitted with a logistic preference function (Appendix 2 Figure 8). The other potential attributes, depth and distance, were not selected by the model. Diagnostics for model fit are not shown here; the objective evaluation of complex models such as SPM has not been resolved statistically and is a subject of current research at Victoria University of Wellington (N. Sibanda, pers.comm.).



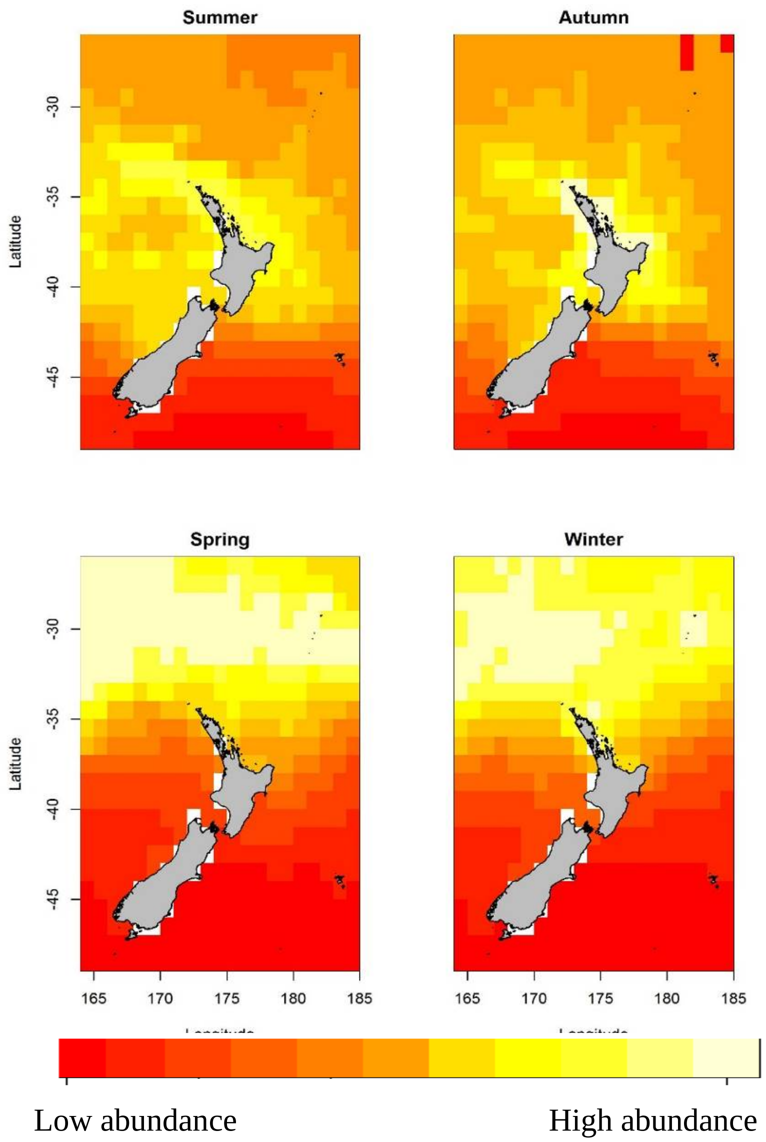
Appendix 2 Figure 8: Estimated preference function from the final model using the estimated functions for Sea Surface Temperature (SST) and Net Primary Productivity (NPP).

The normalised residuals showed structure, and were not particularly good, but were better than obtained for a preliminary model run that lacked spatial structure (null model) (Appendix 2 Figure 9).

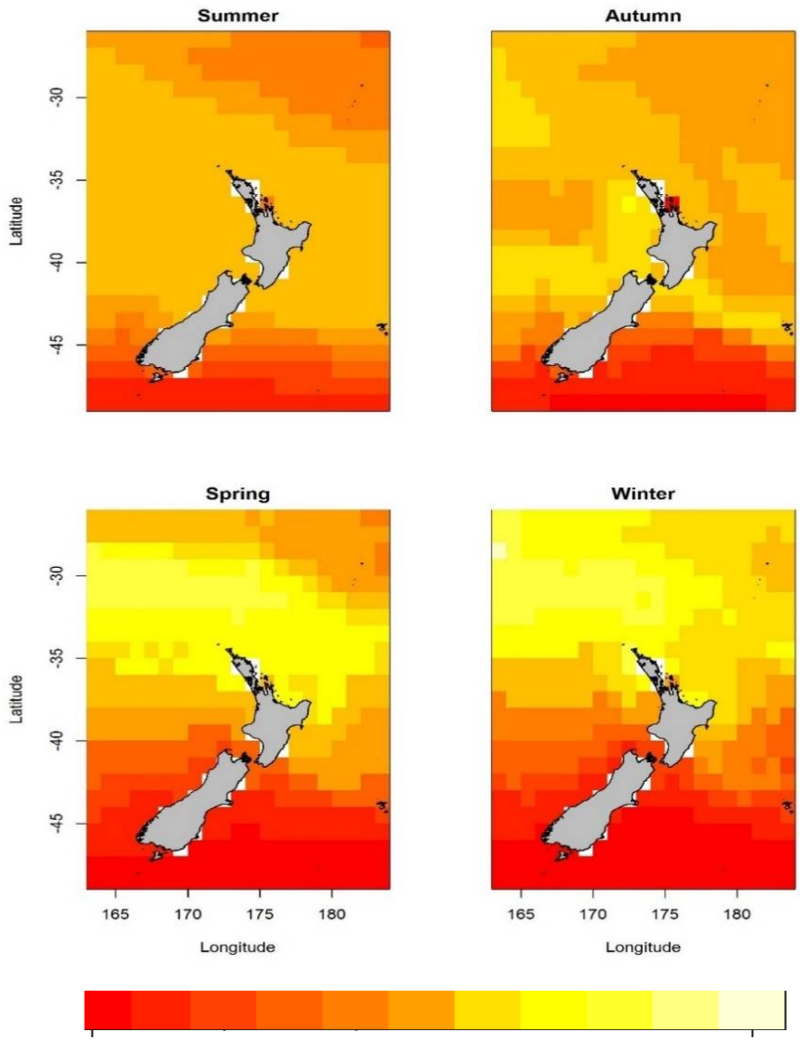
The current and future distribution of estimated preference layers (SST, NPP) were then obtained from the global coupled models (See Appendix B given by Cummings et al. 2017). The predicted relative spatial distributions of albacore in 2012, 2055, and 2100, based upon these layers, are shown in Figures 10–12.



Appendix 2 Figure 9: Normalised residuals by latitude, longitude and year for the final bivariate model.

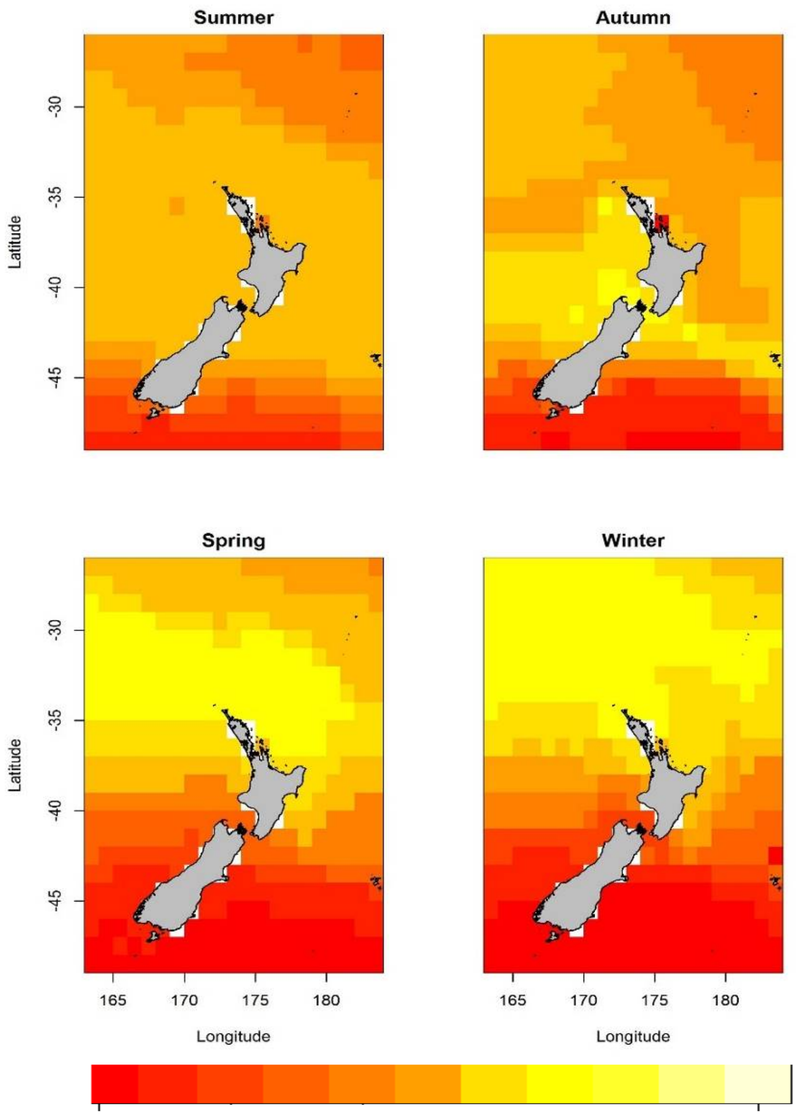


Appendix 2 Figure 10: Expected relative abundance of albacore for the year 2012 presented by season.



Low abundance High abundance

Appendix 2 Figure 11: Projected relative abundance of albacore for the year 2055 presented by season.



Low abundance High abundance

Appendix 2 Figure 12: Projected relative abundance of albacore for the year 2100 by season.

The overall current distribution of the fishery was reasonably well predicted, in that it explained the concentration of the fishery to the northeast of the North Island in summer and autumn, and also the extension of the range to the west of the South Island during these seasons. The fishery to the west of the South Island in autumn has, however, been larger than would be expected given the model predictions. In addition, the model also predicted areas of "preferred habitat" that were not the location of notable fisheries, for example to the west of the North Island. The model did correctly predict few fish on Chatham Rise; there has been no fishery on Chatham Rise despite the *a priori* attractiveness of this productive region (abundance on Chatham Rise was constrained by the SST preference).

The relative distribution of albacore in future years was estimated to be broader and extended further south. The southern boundary of distribution was determined by the SST, and the northern boundary by NPP. The preferred habitat extended over a much wider region, and as a result the relative abundance was lower on average; this was because the number of fish in the model was constant over time, resulting in a lower average density (hence the density extended to "high" in 2012, but only to "medium" in 2100). During the spring and winter of 2012, albacore were predicted to be centred to the north of the North Island, above about 34° south. By 2100, this distribution had shifted south such that relatively high density areas extended around northern New Zealand throughout the winter, to about 36° south. By 2100, the model also predicted that albacore would be caught on Chatham Rise during the autumn.

Discussion

SPM is a relatively complex statistical tool for examining fish distribution and environmental correlates. We note that much of the results could be generated from other correlative studies (Horn et al. 2013). SPM was used here for its ability to add realism through population dynamics, for example, potential distance functions (which limit how fast fish can move). This added realism could, in principle, increase model predictive ability, and forecasting accuracy. Specific evaluation of predictive ability was beyond the scope of this preliminary study. In addition, although this was not done in this study, SPM can model the full dynamic processes of a stock, including stock size and density-dependent variations over time (as it is basically a spatially-extended version of the stock assessment program CASAL). For albacore, making this extension would require modelling the full range (in some way) of the stock, with relevant data and stock parameters; this would be a substantial extension, but could offer predictions not just of where the fish would be and how extensive their preferred habitat would be (as in the present study), but also how numerous they would be and how fishery catch rates might change.

The statistical estimation of parameters for spatially and temporally explicit models is challenging and requires good and numerous data. The model had some difficulty estimating parameters (poor model convergence), and multiple model runs were required to achieve best parameter estimates.

The model SPM appeared to be useful (or at least interesting) in simulating and understanding fish distribution, but additional, more relevant, good quality, and consistent data would improve the veracity of future research efforts. More data are now available than were used in this study and, in particular, consistent data mean that the historical data used to estimate preference layers need to be consistent (i.e., from the same source/model) with that used for future projections. We noted, for example, the large difference in NPP that were obtained from different sources (see Appendix 2 Figures 6 and 7). In this preliminary study, the inconsistency between data used to train and predict was simply because of time limitations; it took a relatively long time to collate and format the environmental layers, and we used what was most readily available. Clearly, inconsistencies in the data used to train the model, and then to make predictions, should ideally be removed.

The most intensive tasks were data compilation and grooming. Once the data are collated and compiled, the actual model runs were a minor component of the research. Once data are compiled, analyses might therefore be extended relatively efficiently to additional species.

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APPENDIX 3: Stakeholder workshop summary

The first stakeholder workshop hosted by this project was entitled '*Climate Change Risks and Opportunities for the Seafood Sector*' and was held on 9 November 2016. The day-long workshop was attended by 27 people (from industry and central government, and scientific experts) with interest in contributing to the project objective of identifying risks and opportunities that are likely to arise for the seafood sector as a consequence of future environmental change in coastal and offshore New Zealand waters. The workshop had three explicit objectives:

- To communicate the aims and scope of this MPI funded project;
- To discuss the initial draft of the Technical Report required for Specific Objective 1(hereafter "draft SO1 Technical Report") on CO_2– and climate–induced changes that may affect fisheries and aquaculture in the New Zealand region, in particular to identify:
    - additional information that can contribute to this preliminary synthesis; and
    - gaps in information required to assess future impacts on New Zealand's seafood sector.
- To explore ways to improve access to and dissemination of technical information on the state of knowledge for fisheries and climate change. What tools will best inform and assist fishers and resource managers in responding to future environmental change?

The workshop morning sessions introduced the project and project team, outlined the objectives of the project, and introduced a range of potential decision support tools to disseminate information and policy and management strategies to address climate change in the fisheries and aquaculture sectors. The draft SO1 Technical Report (Cummings et al. 2016), that had been provided to participants prior to the workshop, was also discussed. After lunch, breakout sessions and a report back session to plenary were used to brainstorm which decision support tools and resources best suit the needs of the New Zealand seafood sector and are most applicable based on the available state of knowledge for New Zealand.

This Appendix, and Section 1 below, summarises the workshop discussions addressing each objective. Progress on additional research required to fill information gaps identified during discussions of the draft SO1 Technical Report are detailed in Section 2 (below) and during sector-specific breakout sessions in Section 3 (below). A summary of the potential technical tools to support dissemination of information on fisheries and climate change are provided in Section 4.

1 Workshop – general points

Mary Livingston (MPI) and Carolyn Lundquist (NIWA) introduced the project and workshop, discussing project objectives and how climate change is viewed and acted upon within the fisheries and aquaculture sector relative to other primary industry sectors in New Zealand. In general, participants suggested that marine industries are well behind efforts at comprehensive understanding of, and adaptation to climate change, compared to terrestrial sectors; specific reference was made to reports on climate change and the agricultural sector (e.g., Parliamentary Commissioner for the Environment 2016). Open discussions with participants included a range of viewpoints, and perceptions on how climate change is perceived in the fisheries sector. For example, one participant suggested that "*Some stakeholders don't believe in climate change at all; other stakeholders don't believe you can do anything about it.*" Other participants showed a desire to understand more, and to be able to prepare for potential climate change effects, with some industry groups (particularly aquaculture and rock lobster fisheries) being particularly concerned about "*what's going to happen, when it is going to happen, and what we can do about it?*" In general, all participants saw identifying risks and opportunities of climate change as valuable for future stability of the fisheries sector.

Building on input of physical scientists who had been involved in preparing IPCC reports, or in Ministry for the Environment research to assess and respond to coastal risk to climate change, conversations covered the 'shelf life' of strategies (i.e., whether the strategy would be a viable option in future decades), that strategies often changed based on the immediacy of climate change impacts, and whether mitigation could forestall these impacts. Concepts of Resistance, Resilience and

Response to climate change were discussed in the context of how different conceptual strategies applied within the fisheries sector. Further discussions also revolved around 'response path dependencies' (i.e., chosen decision-making pathways that then limit or exclude future choices or policies), and the need to plan far enough in the future to avoid a decision-making cul-de-sac, where historical management and industry choices result in a lack of future adaptation options to climate change. A key to understanding and avoiding these potential cul-de-sacs is being aware of where the entry points are for decision making in the fisheries and aquaculture industry in New Zealand. In other words, identifying where it is within the policy or management cycle that decisions are made, or where new information can be applied to inform future decisions or pathways (Figure 9). This concept was discussed with stakeholders during discussions about climate change to facilitate early identification of pathways that help maintain adaptation options. Participants suggested a range of potential venues for these discussions, such as expert workshops to derive information (or information gaps), or inclusion of these discussions in regular MPI working group meetings (Biodiversity Research Advisory Group (BRAG), Aquatic Environment, Shellfish, Deepwater, Antarctic). The latter would increase the engagement of the fisheries sector in both providing fisher/anecdotal input into climate change-fisheries interactions, as well as influencing collection of information to enhance understanding of climate change and fisheries.

Some comments revolved around how the legislation and institutional system could support (or alternatively could be a barrier to) the inclusion of climate change in management decisions. For example, the procedure of setting Total Allowable Commercial Catch (TACC), calculations of B_{MSY} (spawning stock biomass at maximum sustainable yield) and F_{MSY} (fishing mortality at maximum sustainable yield), as well as adjustments to individual fisher quotas are all possible entry points whereby climate change adaptation could be incorporated (Appendix 3 Figure 1). Other adaptation options include fisher behaviour decisions, such as what gear to use, and how, when, and where it is used. Environmental considerations and bycatch mitigation can also be entry points by which climate change could be incorporated into fisheries decision making, for example, through inclusion of different environmental scenarios in stock assessments to represent different possible climate change scenarios and their implication for fisheries. Examples discussed included individual species sectors that were (i) perceived to be responsive and could serve as examples of successful management models (e.g., rock lobster), or (ii) where climate change or environmental variability had been utilised in stock assessments (e.g., school shark). One participant suggested that the rights-based fishing allocation (quota management system) was particularly primed to actively respond and react to climate change but required strategic direction to make this transition to 'climate changed information decision making'. Others focused on the rigid legislative framework; here the structure of Fisheries Management Areas was perceived as either challenging or prohibitive in adapting to issues such as changes in stock boundaries, or other climate-associated changes that might result in the need to subdivide or amalgamate fisheries areas or reallocate or change quota allocations. Key entry points were seen in the role of science in informing fisheries stock assessments, and the inclusion of climate change drivers at this stage in the decision-making process. Participants agreed that existing fisheries tools and processes could be used, and climate change drivers could be incorporated into them.

Participants disagreed on the level of information deficit relative to the implications of climate change for fisheries management. Some participants suggested that fisheries data were insufficient, for example, for fisheries where recreational catch was a substantial portion of total catch, reliable data on recreational catch and effort necessary to adequately assess the fishery with respect to climate change had not been collected. Other participants suggested that existing data were sufficient but had not been analysed with respect to climate change. Most participants agreed that change was occurring, but typically data were not analysed with respect to climate (e.g., southern blue whiting). Participants suggested that compilation and further analysis of existing data were required to elucidate how and where climate change was already showing changes in fisheries with respect to species distributions. Further, it was suggested that some species may be experiencing range shifts, with the likelihood of whole groups of species moving/shifting distribution together. An example of predictive models of changes in spatial distribution was mentioned, and it was suggested that this type of analysis be included in the SO1 Technical Report (see Section 2.3, *Estimating fish distribution under climate change: investigation of the use of a statistical spatial population model*).

Timelines for climate change were discussed, emphasising that both long-term (e.g., 2100) and short-term (e.g., 5 yearly) implications were required for management. Other modelling tools were introduced (e.g., Atlantis) for which climate modules do exist but have not yet been applied in New Zealand. It was noted that Atlantis models are being developed for Tasman and Golden bays and Chatham Rise, with primary focus on validating a base model against fisheries and trophic information. Further iterations of these Atlantis models could include climate change modules.

2 Summary and suggestions for draft Technical Report

Vonda Cummings (NIWA) introduced and reviewed the content of the draft SO1 Technical Report (Cummings et al. 2016). Key physical drivers (temperature, salinity, circulation, pH, oxygen saturation) were compiled to show national and regional patterns in predicted changes in the marine environment, and to extrapolate these changes to implications for the fisheries sector. Drivers include known climate stressors on fish and shellfish biology such as ocean acidification, as well as changes to the extrinsic operating environment through increases in wind and wave height. Key gaps identified in the draft SO1 Technical Report were a general lack of information across many aspects of fish life history, particularly early life stages. The report also included only limited information of relevance to deep sea (>250 m) fisheries, such as changes in carbonate layer. Existing research projects on climate change were noted, and links to new research results since the release of the draft SO1 Technical Report in June 2016 (Cummings et al. 2016) were identified for inclusion in the updated report. Recent results of a project by Matt Pinkerton (NIWA) were presented, where ocean productivity was estimated via satellite remote sensing and used to estimate predicted reductions in detrital flux to both the water column and the seabed (Pinkerton et al. 2016). Changes in detrital fluxes at 100 m and at the seabed were extrapolated to spatial maps of change in diet of fish species and predicted changes in food available to selected deepwater fish species.

Key recommendations from participants for filling gaps in the draft SO1 Technical Report included requests to provide more information on all aspects of climate change, from physics to fisheries specific information, to mechanisms for climate adaptation (Cummings et al. 2017).

3 Breakout sessions

Afternoon breakout sessions were facilitated to allow in depth discussions with respect to different fisheries sectors, and participants opted to join either a deepwater/inshore fisheries group, or a shellfish/aquaculture group. To guide further development of climate change adaptation tools for the New Zealand fisheries and aquaculture sector, discussion groups considered the following questions:

- What information do you need to manage your fishery for climate change?
- What are key climate change concerns for this sector?
- What are key non-climate change stressors for this sector?
- What barriers do they perceive to adapting to climate change?

Deepwater/Inshore Fisheries Breakout Group

The perception of this breakout group was that climate change was not a priority for deepwater or inshore fisheries, but that there is a strong need to increase awareness to avoid lost opportunities/risks of adverse impacts.

Key entry points to incorporate climate change in management were suggested as:

1. 5 year reporting – include climate change projections. Standard, short timescales – the next Annual Fisheries Plenary Report will include a climate change chapter;
2. Stock assessments – include climate change drivers and scenario implications in stock assessments, and provide for mechanism for industry and experts to suggest key drivers to include in RfPs;
3. Build step of filling research gaps into Fisheries Research Plan; requires justification within cost recovery model.

Key research gaps/issues identified:

- B_{MSY} in legislation is difficult to change. It would be more efficient if the response required to take into account ecosystem regime shifts was included in plans/management to allow immediate action and avoid perceived slow response of current QMS framework. But, note that:

- Marine Stewardship Council certification requires an adjustment in TAC if an ecosystem regime shift is identified;
- The Minister of Fisheries can mandate a management change in response to an ecosystem regime shift (or to anything else);
- It is uncertain how to define time varying B_0, B_0/B_{MSY} to take into account a new ecosystem regime (i.e., need to be able to define regime shift with respect to IPO, PDO, or other regional indicator).

- Requirement for spatial/temporal/trophic coordination of stock assessments for interacting species and recognition of overlaps/connections/shifting boundaries in stock distribution.
- Need for cross agency strategy to link relevant science findings to implications for fisheries management priorities. In other words, use the leverage of relevant research undertaken in other sectors to elevate the effects on fish. Examples of relevant research undertaken in other sectors includes:
  - Environmental Domain Reporting;
  - Funding and priorities of Natural Resources Sector;
  - MBIE Endeavour Fund and Marsden Fund.

Shellfish and Aquaculture Breakout Group

In the shellfish and aquaculture breakout session, the summary of various tools for integrating climate change variables into fisheries management were discussed and considered as possible ways to move to better integration of climate change and adaptation information. However, using them to go forward with the day's group discussion was complicated by a lack of understanding of the details of each and the difference in needs for each participant. However, at least one member of the breakout group was very interested in considering adaptation pathways and triggers (both of which were tools discussed earlier in the day), that could systematically be identified and would lead to informed adaptation action. The group then focused on a foundation question for further discussion: How could climate change challenge a functioning and economical aquaculture industry?

This breakout group opted to focus on a particular species to assist with their discussion, with the working goal to discuss information requirements to maintain a functioning and economically viable green-lipped mussel aquaculture industry. The biggest concern identified by the group was how climate change may increase closure of aquaculture 'grounds' as a result of more frequent contamination with pathogens. The discussion first considered potential impacts of climate vulnerability through exploring climate-linked environmental changes and possible species population response, and then discussed triggers that could be practical to the green-lipped mussel aquaculture industry and subsequent adaptation actions. In the time available the group was able to 1) identify aspects of the green-lipped mussel aquaculture industry's vulnerability to climate change, 2) identify examples of useful triggers and adaptation actions, and 3) identify the kinds of information, monitoring data, or model data that could help inform those triggers.

Some environmental changes influenced by climate change and potential impacts to green-lipped aquaculture industry function and economic viability were identified:

- Changes in land-based runoff (precipitation changes, timing, extremes) causing:
  - Potential increase in human waste pathogen contamination due to increased land-based runoff. This is currently a significant challenge and can prevent harvest and sale of shellfish due to contamination. The viability of an aquaculture site is compromised when contamination is frequent;
  - Increases in other or new pathogen impact due to a changing climate;
  - Water quality challenges due to increased suspended sediment inputs from land erosion.
- Changes in coastal water temperature, circulation and condition causing:
  - Detrimental algal blooms;
  - Increased bio-fouling;

- Decreased carrying capacity due to food web changes;
  - Decreased mussel spat survival;
  - Changes in ideal siting for aquaculture; permitting is site specific and moving is difficult;
  - Decreases in overall suitable farmable space.

Species population changes influenced by climate change and potential impacts on green-lipped aquaculture industry function and economic viability were also identified. These included effects on:

- Mussel spat dynamics
  - Availability - changes in natural abundance;
  - Mussel spat capture success;
  - Mussel spat retention after capture.
- Productivity
  - Survival;
  - Growth rates;
- Environmental suitability
  - Aquaculture location;
  - Changes in viable species.

The breakout group then considered adaptation action triggers and the information required to address potential impacts of climate change to green-lipped mussel industry function and economic viability. These included:

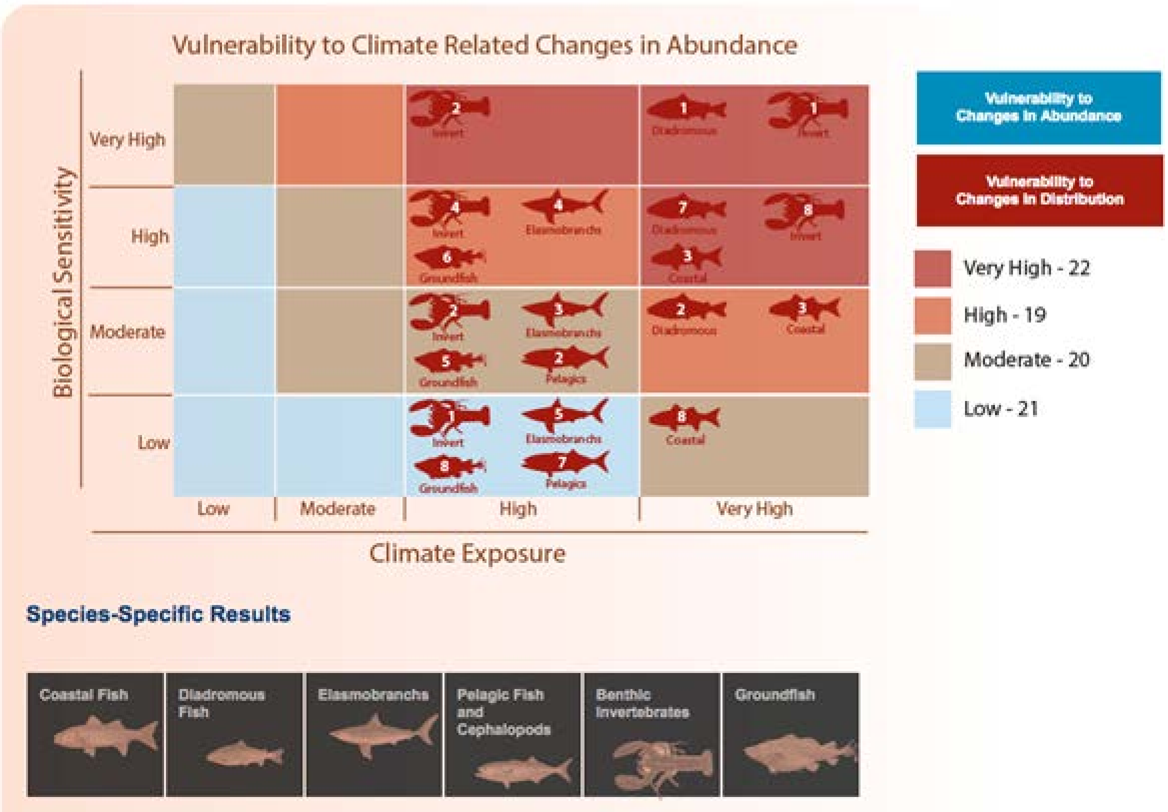
- Adaptation Action Triggers
  - Change in coastal currents or state of coastal water;
  - Change (increase) in land-based runoff;
  - Change in sediment transport
- Adaptation Actions Considered (including some consideration of the information needed)
  - If pathogen risk increases, invest in research to better identify pathogens, understand sources of pathogens and links to environmental change;
  - If resulting pathogen persistence leads to more frequent 'grounds' closure, invest in research to better understand why and where this is occurring to better site future aquaculture installations;
  - As above, invest in research to better predict when contamination may occur to prioritise harvest before contamination occurs.

4 Climate change decision-support tools

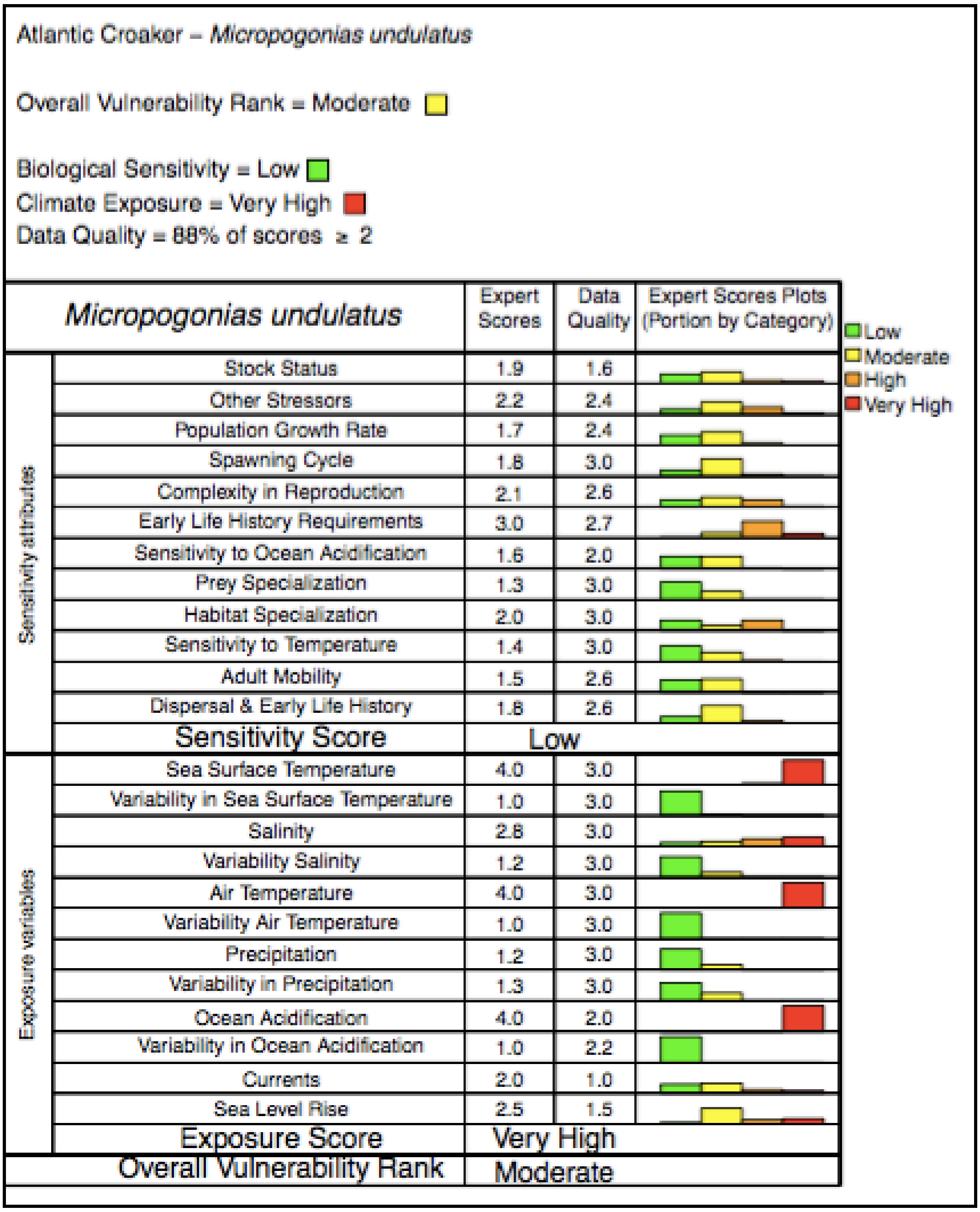
Internationally, a range of tools have been used to support dissemination of information about climate change to the fisheries sector. A session led by Lara Hansen (EcoAdapt, USA) introduced many of these tools, to inform discussions on what type of tool was useful to the New Zealand fisheries and aquaculture sector, as well as what data are available to parameterise these tools. Tools were categorised as those that (i) identify areas/regions/sectors of vulnerability to climate change impacts; (ii) support information dissemination and development of response pathways; and (iii) assist in the identification of thresholds and triggers of climate change related effects that will require management action. Some examples of tools were introduced:

- North Pacific Fisheries Management Council example of fisheries adaptation that used a pre-cautionary approach in data limited regions. In Arctic waters, where not enough information is known to evaluate or perform stock assessment, no fishing is allowed;
- The U.S. National Oceanic and Atmospheric Administration (NOAA) Regional Adaptation Plans which include climate strategies;
- Washington State (USA) shellfish aquaculture ocean acidification example, where data uncertainty, potential thresholds and contingencies were applied to a management tool to incorporate climate change into decision making;

- NOAA vulnerability scorecard tool; scorecards (report cards) and methodologies and results are provided on a publicly accessible website (Morrison et al. 2015). This assessment (either as species or as regional assessment findings) can be done using a simplified matrix of sensitivity and exposure derived from the larger Rapid Risk Assessment to compare sensitivity across species in each fisheries management region (Appendix 3 Figure 1, Appendix 3 Figure 2);
- Rapid vulnerability assessment tool (examples include case studies in Canada, US, Mexico Commission for Environmental Cooperation) (e.g., summary from a rapid risk assessment process for coastal ecosystems in California (USA) Appendix 3 Table 1; Hansen et al. 2017). This one-day rapid risk or vulnerability assessment approach can be used to establish relative vulnerability of selected marine habitats or species groups.
- Decision support flowchart tools, e.g., NOAA: toolkit.climate.gov. Here, the results of a risk assessment can be used to create decision support tools to guide managers in planning for different conditions or scenarios. A model that could easily apply to New Zealand marine fisheries used this process to develop a 3-step approach (Appendix 3 Figure 3, Appendix 3 Figure 4).
- Fisheries management dashboard on Climate Adaptation Knowledge Exchange website (CAKEx.org).



Appendix 3 Figure 1: Example Regional Summary used by U.S. National Oceanic and Atmospheric Administration (Morrison et al. 2015; Hare et al. 2016). This version sourced from https://www.fisheries.noaa.gov/new-england-mid-atlantic/climate/northeast-vulnerability-assessment



Atlantic Croaker – *Micropogonias undulatus*

Overall Vulnerability Rank = Moderate

Biological Sensitivity = Low
Climate Exposure = Very High
Data Quality = 88% of scores ≥ 2

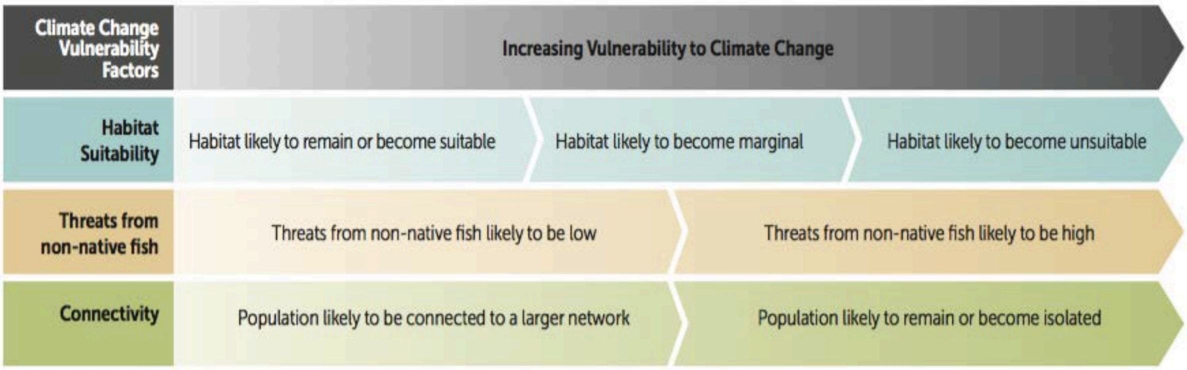
	Micropogonias undulatus	Expert Scores	Data Quality	Expert Scores Plots (Portion by Category)
Sensitivity attributes	Stock Status	1.9	1.6	
	Other Stressors	2.2	2.4	
	Population Growth Rate	1.7	2.4	
	Spawning Cycle	1.8	3.0	
	Complexity in Reproduction	2.1	2.6	
	Early Life History Requirements	3.0	2.7	
	Sensitivity to Ocean Acidification	1.6	2.0	
	Prey Specialization	1.3	3.0	
	Habitat Specialization	2.0	3.0	
	Sensitivity to Temperature	1.4	3.0	
	Adult Mobility	1.5	2.6	
	Dispersal & Early Life History	1.8	2.6	
	Sensitivity Score	Low		
Exposure variables	Sea Surface Temperature	4.0	3.0	
	Variability in Sea Surface Temperature	1.0	3.0	
	Salinity	2.8	3.0	
	Variability Salinity	1.2	3.0	
	Air Temperature	4.0	3.0	
	Variability Air Temperature	1.0	3.0	
	Precipitation	1.2	3.0	
	Variability in Precipitation	1.3	3.0	
	Ocean Acidification	4.0	2.0	
	Variability in Ocean Acidification	1.0	2.2	
	Currents	2.0	1.0	
	Sea Level Rise	2.5	1.5	
	Exposure Score	Very High		
	Overall Vulnerability Rank	Moderate		

Appendix 3 Figure 2: Example individual species data to support Regional Summary used by U.S. National Oceanic and Atmospheric Administration (Morrison et al. 2015; Hare et al. 2016).

Appendix 3 Table 1: Example summary of a Rapid Risk/Vulnerability Assessment Tool (Hansen et al. 2017). SLR = sea level rise, OA = Ocean acidification, ENSO = El Niño–Southern Oscillation, PDO = Pacific Decadal Oscillation.

Habitats	Climate Stressors	Non-climate stressors	Responses	Adaptive capacity (AC) (strength/weakness)
Rocky Intertidal, Kelp Forest, Deep sea floor	SLR, wave action & erosion, Weather changes, Increased water temperature, OA, ENSO/PDO, Decreased dissolved oxygen, Upwelling	Marine-source pollution & spills, Invasive species, Harvest, Disease, Land-source non-nutrient pollution, Microplastics/ compounds of concern.	1. Habitat protection (via fisheries regulations and visitation) 2. Document vertical range shifts via citizen science 3. Support establishment of lost natural species 4. Enhance scientific knowledge (OA, seafloor mapping, microplastics) 5. Prevent invasive introductions (public education) 6. Improve evaluation of current management action 7. Fishery regulations (expand no-take reserves/ essential fish habitat)	Filled out AC section as-is. All habitats: moderate to high intrinsic AC, but factoring in organizational capacity/efficacy (extrinsic) decreased overall AC. Lower AC for deep-sea floor due to "value/importance" when considering public rather than ecosystem value.

Appendix 3 Figure 3: Process to develop decision support tables (Nelson et al. 2016).



Appendix 3 Figure 4a: Step 1 in the development of decision support tables: Assessing risk or vulnerability of selected species to climate change (Nelson et al. 2016).

STEP 2: Use Vulnerability Matrix to Clarify Management Goals and Select Climate Adaptation Strategies

		HABITAT REMAINS OR BECOMES SUITABLE	HABITAT BECOMES MARGINAL	HABITAT BECOMES UNSUITABLE
POPULATION IS CONNECTED TO A LARGER NETWORK	LOW THREAT FROM NON-NATIVE FISH	1 **Relative vulnerability to climate change:** Low **Relative value for native salmonid conservation:** High value in both the short and long term **Potential Goal:** Protect and maintain (or improve if warranted) this habitat network for long-term conservation of native salmonids **Strategies:** • Protect climate refugia; • Protect existing networks; • Expand/refound populations; • Prevent invasion of non-native fish	2 **Relative vulnerability to climate change:** Medium **Relative value for native salmonid conservation:** Potential value over the long term, but will likely require investment to moderate climate impacts **Potential Goal:** Improve the suitability of this habitat network for long-term conservation of native salmonids **Strategies:** • Moderate stream temperature increases; • Moderate base flow decreases; • Moderate peak flow increases; • Increase adaptive capacity of native fish; • Minimize adverse impacts in the event of potential increased wildland fire disturbance; • Protect existing networks; • Reduce uncertainty through research and monitoring; • Prevent invasion of non-native fish	3 **Relative vulnerability to climate change:** Medium-High **Relative value for native salmonid conservation:** Potential value in the short term to help with population recovery, maintenance of genetic diversity and/or local adaptations; Longer-term value is lower due to decreasing habitat suitability **Potential Goal:** Maintain population in the short-term; In the longer-term, consider facilitating the movement of current population to other locations with more suitable conditions, facilitating the transition of the location to a new state, and/or managing the location for other targets (e.g., game fish or non-fish targets) **Strategies:** • Reduce uncertainty through research and monitoring; • Increase adaptive capacity of native fish; • Relocate individuals to areas likely to remain or become suitable; • Facilitate transition to a new state
	HIGH THREAT FROM NON-NATIVE FISH	4 **Relative vulnerability to climate change:** Medium-Low **Relative value for native salmonid conservation:** High value in both the short and long term, but may require investment to prevent/remove/suppress non-native fish **Potential Goal:** Prevent invasion of non-native fish (or remove/suppress if already present) and protect and maintain (or improve if warranted) this habitat network for long-term conservation of native salmonids **Strategies:** • Remove/suppress non-native fish; • Prevent invasion of non-native fish; • Expand/refound populations; • Protect existing networks; • Protect climate refugia	5 **Relative vulnerability to climate change:** Medium-High **Relative value for native salmonid conservation:** Potential value over the long term, but will require a high-level of investment to both moderate climate impacts and prevent/remove/suppress non-native fish **Potential Goal:** Prevent invasion of non-native fish (or remove/suppress if already present), and improve the suitability of this habitat network for long-term conservation of native salmonids **Strategies:** • Moderate stream temperature increases; • Moderate base flow decreases; • Moderate peak flow increases; • Increase adaptive capacity of native fish; • Remove/suppress non-native fish; • Prevent invasion of non-native fish; • Minimize adverse impacts in the event of potential increased wildland fire disturbance; • Protect existing networks; • Reduce uncertainty through research and monitoring	6 **Relative vulnerability to climate change:** High **Relative value for native salmonid conservation:** Potential value in the short term to help with population recovery, maintenance of genetic diversity and/or local adaptations, but will require investment to prevent/remove/suppress non-native fish; Longer-term value is lower due to decreasing habitat suitability **Potential Goal:** Facilitate the movement of current population to other locations with more suitable conditions; Facilitate the transition of the location to a new state; Consider managing the location for other targets (e.g., game fish or non-fish targets) **Strategies:** • Reduce uncertainty through research and monitoring; • Relocate individuals to areas likely to remain or become suitable; • Facilitate transition to a new state; • Determine additional strategies after clarifying management goal(s)

Appendix 3 Figure 4b: Step 2 in the development of decision support tables: Use a Vulnerability Matrix to clarify management goals and select adaptation strategies (Nelson et al. 2016).

STEP 2: Use Vulnerability Matrix to Clarify Management Goals and Select Climate Adaptation Strategies (cont.)

		HABITAT REMAINS OR BECOMES SUITABLE	HABITAT BECOMES MARGINAL	HABITAT BECOMES UNSUITABLE
POPULATION REMAINS OR BECOMES ISOLATED	LOW THREAT FROM NON-NATIVE FISH	**Relative vulnerability to climate change:** Medium-Low **Relative value for native salmonid conservation:** Potential value for providing genetic diversity and/or local adaptations in both the short and long term, but will likely require investment to address fragmentation **Potential Goal:** Evaluate representativeness of this population across the landscape, and determine what level of protection/reconnection to other habitats is warranted **Strategies:** • Reconnect fragmented networks; • Protect climate refugia; • Minimize adverse impacts in the event of potential increased wildland fire disturbance; • Expand population; • Prevent invasion of non-native fish	**Relative vulnerability to climate change:** Medium **Relative value for native salmonid conservation:** Potential value for providing genetic diversity and/or local adaptations, but will likely require investment to moderate climate impacts and address fragmentation **Potential Goal:** Evaluate representativeness of this population across the landscape, and determine what level of protection/restoration/active management is warranted **Strategies:** • Reconnect fragmented networks; • Moderate stream temperature increases; • Moderate base flow decreases; • Moderate peak flow increases; • Increase adaptive capacity of native fish; • Minimize adverse impacts in the event of potential increased wildland fire disturbance; • Reduce uncertainty through research and monitoring; • Prevent invasion of non-native species	**Relative vulnerability to climate change:** Medium-High **Relative value for native salmonid conservation:** Potential value in short-term for providing genetic diversity and/or local adaptations, but will likely require investment to address fragmentation; Longer-term value is lower due to decreasing habitat suitability **Potential Goal:** Maintain population in the short-term; In the longer-term, consider facilitating the movement of current population to other locations with more suitable conditions, facilitating the transition of the location to a new state, and/or managing the location for other targets (e.g., game fish or non-fish targets) **Strategies:** • Reduce uncertainty through research and monitoring; • Increase adaptive capacity of native fish; • Relocate individuals to areas likely to remain or become suitable; • Facilitate transition to a new state
	HIGH THREAT FROM NON-NATIVE FISH	**Relative vulnerability to climate change:** Medium **Relative value for native salmonid conservation:** Potential value, but may will likely require investment to prevent/remove/suppress non-native fish and address fragmentation **Potential Goal:** Evaluate representativeness of this population across the landscape, and determine what level of protection, reconnection to other habitats, and management on non-native fish is warranted **Strategies:** • Reconnect fragmented networks; • Protect climate refugia; • Minimize adverse impacts in the event of potential increased wildland fire disturbance; • Expand population; • Prevent invasion of non-native fish	**Relative vulnerability to climate change:** Medium-High **Relative value for native salmonid conservation:** Lower value, and will likely require a high-level of investment to moderate climate impacts, prevent/remove/suppress non-native fish, and address fragmentation **Potential Goal:** Facilitate the movement of current population to other locations with more suitable conditions; Facilitate the transition of the location to a new state; Consider managing the location for other targets (e.g., game fish or non-fish targets) **Strategies:** • Reduce uncertainty through research and monitoring; • Relocate individuals to areas likely to remain or become suitable; • Facilitate transition to a new state; • Determine additional strategies after clarifying management goal(s)	**Relative vulnerability to climate change:** High **Relative value for native salmonid conservation:** Low value **Potential Goal:** Facilitate the movement of current population to other locations with more suitable conditions; Facilitate the transition of the location to a new state; Consider managing the location for other targets (e.g., game fish or non-fish targets) **Strategies:** • Reduce uncertainty through research and monitoring; • Relocate individuals to areas likely to remain or become suitable; • Facilitate transition to a new state; • Determine additional strategies after clarifying management goal(s)

Appendix 3 Figure 4b (cont.): Step 2 in the development of decision support tables: Use a Vulnerability Matrix to clarify management goals and select adaptation strategies (Nelson et al. 2016).

Strategy	Objective	Example Actions
Expand/refound populations	Increase population size and number of populations to recover large, interconnected populations	• Expand populations at or below minimum viable population size • Refound new populations in areas expected to be climatically suitable
Facilitate transition to a new state	Allow colonization by new species that may be better suited to new environments and still provide some ecological function and value	• Remove barriers to invasion • Introduce new species
Increase adaptive capacity of native fish	Increase resilience of native fish populations to warming stream temperatures and flow changes	• Identify and restore "warm-adapted" populations of native trout • Consider limiting angler pressure on native fish in streams that are at or near temperature thresholds • Replicate and supplement native fish populations • Remove non-native fish
	Increase native fish health	• Increase public education to eliminate disease vectors • Treat or remove infected/diseased fish • Eliminate or control pollutants or contaminants
	Conserve genotypic/phenotypic diversity	• Conserve or restore a diverse representation of habitats across river basins • Maintain large population sizes to minimize loss of genetic variability and adaptive potential.
Minimize adverse impacts in the event of potential increased wildland fire disturbance	Identify and minimize negative effects to areas most vulnerable to fire impacts	• Develop a geospatial layer of debris flow potential for pre-fire planning • Manage natural fuel conditions and unplanned wildfire effects through fuel management actions and/or use of unplanned wildfire ignitions to minimize negative effects (severity and extent) of fire.
	Restore areas adversely affected by fire	• Inventory disturbed areas for candidate sites for riparian and upland vegetation restoration • Restore and re-vegetate burned areas to store sediment and maintain channel geomorphology
Moderate base flow decreases	Restore or replicate stream flows	• Remove or breach dams • Increase storage of water in floodplains by encouraging natural flooding and groundwater infiltration • On regulated streams, pulse flows during critical times, sourcing from lower in the thermocline
	Reduce water withdrawals and/or water diversions	• Increase efficiency of irrigation techniques • Explore potential to combine sprinkler and flood irrigation to capture increasing spring floods (and recharge groundwater supplies) and then switch to more efficient sprinkler irrigation when stream flows are lower • Consider alternative water supplies for public land operations to retain in-stream flows • Legally secure water rights/agreements for in-stream flows • Reform water laws to enable increased acquisition of in-stream water rights • Explore the use of water trusts/funds to increase investments in the protection of watershed health and function • Use water pricing to encourage water conservation • Where water diversions exist, ensure fish ladders avoid entrainment of native trout
	Restore riparian vegetation	• Establish native riparian vegetation • Remove non-native riparian vegetation
	Increase natural water storage in groundwater aquifers	• Reintroduce beaver and/or install artificial beaver-mimic dams where compatible with fish conservation goals • Increase off-channel habitat and protect refugia in side channels • Protect wetland-fed streams which maintain higher summer flows • Maintain/restore forest and wetland vegetation cover • Reduce road density

Appendix 3 Figure 4c: Step 3 in the development of decision support tables: Select actions to implement selected strategies (Nelson et al. 2016).

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