FIS028 - FIS workshop on Global synthesis of climate impacts on fish distribution and growth and implications for Scottish fisheries

A REPORT COMMISSIONED BY FIS
AND PREPARED BY

The University of Aberdeen

Published by: Fisheries Innovation Scotland (FIS)

This report is available at: http://www.fiscot.org.

Dissemination Statement

Disclaimer

Suggested Citation: Marshall C. T., Baudron A. R., Fallon N. G., Spencer P. 2019. FIS workshop on Global synthesis of climate impacts on fish distribution and growth and implications for Scottish fisheries. A study commissioned by Fisheries Innovation Scotland (FIS) http://www.fiscot.org/

Title: FIS workshop on Global synthesis of climate impacts on fish distribution and growth and implications for Scottish fisheries

ISBN: 978-1-911123-17-0

First published: July 2019

European Maritime
and
Fisheries Fund

The Scottish
Government
Riaghaltas na h-Alba

FIS workshop on *Global synthesis of climate impacts on fish distribution and growth and implications for Scottish fisheries*

Final report

C. Tara Marshall*, Alan R. Baudron*, Niall G. Fallon*, and Paul Spencer+

with contributions from workshop participants

*University of Aberdeen, UK, + National Marine Fisheries Service/Alaska Fisheries Science Centre, Seattle, USA

June 2019

FIS workshop participants at the University of Aberdeen November 28 2019

Table of Contents

Executive Summary iv

List of Acronyms vi

1 Introduction 1

- 1.1 Scientific background 1
- 1.2 Industry perception of climate change 2
- 1.3 Impacts of climate change on fisheries policy and vulnerability 3
- 1.4 Adapting to climate change 3
- 1.5 Aims of the FIS028 4

2 Organisation of FIS028 5

- 2.1 Organisation of the workshop 5
- 2.2 Organisation of the public event 6
- 2.3 Live-streaming and recording of the workshop and public event 7
- 2.4 Print media 8
- 2.5 Organisation of this report 11

3 Climate change impacts on fish distribution 11

- 3.1 Review of climate impacts on spatial distribution 12
  - 3.1.1 Australia 12
  - 3.1.2 UK & Europe 13
  - 3.1.3 US 14
    - 3.1.3.1 West coast US and Alaska 14
    - 3.1.3.2 East coast US 15
  - 3.1.4 Summary of insights gained by comparing evidence of changing distribution for three regions 15
- 3.2 Management implications of changing fish distributions in EU waters 16
- 3.3 Methods used for analysis of distributional data for fish 17
  - 3.3.1 Empirical measures of species distribution 17
  - 3.3.2 Habitat suitability models 18
  - 3.3.3 Generalized additive models 19
  - 3.3.4 Climate attribution and skill testing 19
  - 3.3.5 Citizen science initiatives 20
  - 3.3.6 Other methods 20

4 Climate change impacts on individual fish growth 20

- 4.1 Review of climate impacts on individual growth rates 21

4.1.1 Australia 21
4.1.2 UK 26
4.1.3 US 30
4.1.3.1 West coast US and Alaska 30
4.1.4 Summary of insights gained by comparing evidence of changing growth rates for three regions 33
4.2 Management implications of changes in fish growth 33
4.2.1 Yield 33
4.2.2 Bioeconomics 34
4.2.2.1 Size-targeting and products in the Bering Sea pollock catcher processor fishery 34
4.2.2.2 Products, vessels, and trip length in the Bering Sea pollock inshore fishery 34
4.3 Data available for modelling individual growth rates 35
4.3.1 European and Nordic databases for analysing growth 35
4.3.1.1 Europe 35
4.3.1.2 Norway 36
4.3.1.3 Iceland 37
4.3.2 US databases for analysing growth 37
4.3.2.1 Alaska Region 37
4.3.2.2 California Current Ecosystem 38
4.3.2.3 Gulf of Mexico 38
4.4 Methods of analysing growth data for fish 39
4.4.1 State-space models 39
4.4.2 Dynamic factor analysis 41
4.4.3 Linking ocean conditions to growth 41
4.4.4 Effects of climate on individual growth variability of fish in the North Pacific Ocean . 42
4.4.5 Across-species comparison of growth and body size in marine fish from polar to tropical regions 43
4.4.6 Mixed-effects models 44
5 Adaptation to climate change 45
5.1 Australia 45
5.2 UK 49
5.2.1 Climate change risk assessment 50
5.2.2 National Adaptation Programme 50
5.2.3 Reporting Authority 52
5.2.4 The Economics of Climate Resilience report 53

5.2.5 UK Marine Climate Change Impacts Partnership (MCCIP) 53

5.2.6 Marine Climate Change Centre (MC3) 54

5.3 US 54

5.3.1 National overview of adaptation plans 54

5.3.2 Ecosystem-based adaptation planning for Alaskan fisheries 55

5.4 Comparing and contrasting the approaches taken to adaptation planning in Australia, UK and US 55

6 Insights about climate change impacts on fish from comparing Australia, UK and UK 56

7 Recommendations relevant to Scottish fishing industry 58

7.1 Knowledge gaps 58

7.1.1 Biological knowledge gaps 58

7.1.2 Industry-focussed knowledge gaps 59

7.2 Barriers to knowledge development and exchange 60

7.3 Raising awareness about climate change in the fishing industry 61

8 Scientific Objectives of the FIS Workshop 61

8.1 Manuscript about changes in distribution 61

8.2 Manuscript about changes in growth 62

8.3 Manuscript on global meta-analysis of fish growth 62

8.4 Panopto presentations 62

9 Acknowledgements 62

10 References 64

11 Appendices 76

11.1 Appendix 1: Description of EU Project CERES - Climate Change and European Aquatic Resources 76

11.2 Appendix 2: Species on the Move abstract (Marshall et al.) 79

11.3 Appendix 3: ICES Annual Science Conference 2019 abstract (Spencer et al.) 80

Executive Summary

The aim of FIS028 was to determine whether the spatial distribution and individual growth rates of marine fish show a coherent set of responses globally that are consistent with physiological, ecological and logical expectations. If so, then this knowledge could provide a firm foundation for forecasting the impacts of future climate warming in Scottish waters and elsewhere. Experts from the UK, Australia, US, Canada, Norway, Iceland, Denmark, and Germany attended a 5-day workshop with eight scientists from US, Canada, Australia, and Chile participating in workshop discussions remotely. Recognising the importance of communicating current scientific knowledge in an accessible way, a public event was held to share global and local perspectives on the impacts of climate change on distribution, productivity and management of commercial fish stocks. The discussions resulted in a range of general insights about climate impacts on fish distribution and growth, including how the fishing industry will need to adapt, that are summarised below.

Global evidence of distributional shifts There is ample evidence of changes in the distribution of marine species occurring worldwide that generally, but not always, result in shift poleward and/or towards deeper waters. These distributional changes are often associated with warming, although the occurrence of density-dependent habitat selection, and the impact of fishing pressure were also noted to affect distribution. Improving data collection and reporting of fish distribution would contribute towards our understanding of distribution changes of commercial marine species.

Global evidence on changes in individual growth There is limited but growing support for temperature impacts on growth rates of individual that are consistent with the physiological expectation that warmer waters result in smaller adult body sizes. Consequently, there has likely been unrecognised, climate-driven declines in yield of commercial fish stocks in regional seas that have already experienced strong warming trends.

Differential vulnerability of fish stocks to climate change Quantitative vulnerability assessments are being used to describe risks and identifying priority stocks for conservation or adaptation measures. Global-scale assessments of the vulnerability of marine resources suggests that the vulnerability of UK fisheries resources is small compared to other regions. On more regional scales, vulnerability analyses are useful for identifying commercial stocks that should be prioritised for adaptation planning.

Vulnerability of fishing industry to storminess There is evidence suggesting that frequency and intensity of storms will increase in the Northeastern Atlantic. The vulnerability of fisheries to changes in storminess is unclear at present. Vulnerability assessments for specific fishing industries should be examined by incorporating appropriate measures of exposure, sensitivity and adaptive capacity to storms.

Policy adaptation A research base is developing to prepare ocean governance, specifically policy, for the reality of climate-driven shifts in distribution of fish resources. It would be useful to explore the range of policy levers that are available to deal with this problem and summarise global experience.

Economic and structural drivers of adaptation Climate effects on fisheries can be complex because they arise from different physical, biological and economic drivers and different fleets react differently to these drivers. Scenario modelling using available economic data could be

used to identify different adaptation pathways specific for different fleets conditioned on the most likely biological impacts.

Bottom-up versus top-down approaches to adaptation Approaches to national adaptation planning were reviewed for Australia, UK and US. These examples differed in the degree to which there was a centralised national approach and how feasibility of various adaptation options were evaluated.

Salience of climate change to the fishing industry In general fishers perceive climate change to operate on time scales that are too long to be of relevance to day-to-day operations. An example from Australia illustrated how quickly the attitude of fishers could change when presented with first-hand experience of extreme weather events and scientific knowledge that is communicated effectively.

Innovation in developing an evidence base for tracking climate change The fishing industry generates a wealth of standardised information that has yet to be fully captured by scientists. For example, industry-generated roe data has yielded valuable evidence of shifts in spawning times of North Sea cod. It would be useful to consider future data needs so that appropriate databases can be developed.

Workshop discussions identified key knowledge gaps specific to Scottish fisheries that could be targeted in future FIS-commissioned research. The top three recommendations for biological knowledge gaps were considered to be: 1) greater understanding of the likely impacts of climate change on future fish yields in the North Sea; 2) assessing the vulnerability of different species; and 3) investigating the impacts of ocean acidification. The top three recommendations for industry-specific knowledge gaps were considered to be: 1) reconstructing the distributional trends in historical catch data from Scottish logbook information; 2) informing the fishing industry about impacts of climate warming on Scottish fisheries; and 3) surveying industry perceptions about climate change to provide a baseline about current attitudes.

The workshop developed key goals for future research and publications. Towards these, conference presentations will be given at the international Species on the Move conference (July 2019) and the ICES Annual Science Conference (September 2019). Workshop participants are also organising a dedicated ICES working group to continue the research into the impacts of global warming on fish growth with the longer term aim of evaluating the effects on fisheries yields.

List of Acronyms

ARP - Adaptation Reporting Power
ALKs - Age-Length Keys
ACLIM - Alaska Climate Integrated Modeling project
ACC - Alaska Coastal Current
AFSC - Alaska Fisheries Science Center
AI - Aleutian Islands
BSAI - Bering Sea/Aleutian Islands
CC - California Current
Cefas - Centre for Environment, Fisheries and Aquaculture Science
CERES - Climate Change and European Aquatic Resources project
CCRA - Climate Change Risk Assessment
CFP - Common Fisheries Policy
CPUE – Catch per unit effort
Defra - Department for Environment, Food and Rural Affairs (UK)
DEB - Dynamic Energy Budget
DFA - Dynamic Factor Analysis
EBS - Eastern Bering Sea
EDF - Empirical distribution functions
EEZ – Exclusive Economic Zone
EU - European Union
GAM - Generalized additive models
GOA - Gulf of Alaska
ICES – International Council for the Exploration of the Sea
IBMs - Individual-based models
IPCC - Intergovernmental Panel on Climate Change
MC3 - Marine Climate Change Centre
MCCIP - Marine Climate Change Impacts Partnership
MSY - Maximum Sustainable Yield
MEI - Multivariate Enso Index
NAP - National Adaptation Plans
NWFSC - North West Fisheries Science Center
PDO - Pacific Decadal Oscillation
PICES - North Pacific Marine Science Organisation
SDG – Sustainable development goals
SST – Sea Surface Temperature
TSR - Temperature size rule
TAC - Total Allowable Catch
UKNAP – UK National Adaptation Programme

1 Introduction

This project responded to the FIS028 call ***Workshop on fisheries resilience / response to climate change***. The call noted that: "*shifting of the geographical location of fish stocks is an important topic for Scottish fisheries. It may be in response to climate change and/or other factors. Emerging zonal attachment discussions imply that a better understanding of such shifts would be helpful, as would be the development of innovative tools to improve the utility of existing and new fish distribution data*." FIS therefore proposed the organisation and delivery of a workshop to explore the current state of knowledge in these areas, and to identify developments for the future. FIS requested that the primary focus of the workshop should be on climate change and its implications for Scottish fisheries, but the workshop should also consider broader topic of innovation in the use of fish distribution data, harnessing this in the context of emerging zonal attachment discussions.

As described in the project proposal for FIS028, this project is based on the premise that reviewing the global evidence describing climate impacts on the spatial distribution and growth of fish is the necessary precursor to developing statistical models that are capable of robustly forecasting the impacts of climate change on commercial fish stocks. The aim of the project was therefore to determine whether spatial distribution and individual growth rates of fish show a coherent set of responses on a global scale that are broadly consistent with physiological (e.g., fish do not grow as large in warm water), ecological (e.g., boreal fish species shift their distribution northward) and logical (e.g., trends observed in cooling regions will be opposite to those observed in warming regions) expectations. If the physiological, ecological and logical responses are coherent across a wide range of ecosystems then this reduces uncertainty about climate change impacts on fish and creates a firmer basis for developing models for forecasting future responses to climate change at regional scales. As Australia, US and UK can be considered at the forefront of knowledge generation, we secured participation of leading experts from these three countries. Having this international-scale expert perspective was judged to be crucial to informing the regional-scale (i.e., Scottish) perspective.

1.1 Scientific background

The publication of the landmark report by the UN Intergovernmental Panel on Climate Change (IPCC) released on 8 October 2018 (https://www.ipcc.ch/sr15/) focussed public attention on climate change to an unprecedented degree. In that report the world's leading climate scientists warned that there is only 12 years to keep global temperature increases to a maximum of 1.5°C to avoid catastrophic environmental breakdown.

Oceans are a focus of intensive research given their role as a heat sink for the planet (Hoegh-Guldberg and Bruno 2010). On a global scale, temperatures in regional seas have exhibited differential trends over decadal time scales (Belkin 2009). Several regional seas have cooled while others do not exhibit directional trends but fluctuate between cold and warm periods. Conversely, some regional seas are warming very rapidly while others exhibit moderate or slow warming. Relative to other regions, the North Sea is a global hotspot of global warming having undergone ca. 2°C over the past four decades. Comparing the biological and ecological responses to warming in the North Sea with the responses detected in other areas, exhibiting either similar and different temperature trends over time, is an important way of confirming whether the observed responses are coherent in the sense of being consistent with our physiological, ecological and logical expectations of temperature effects on life histories (Horne et al. 2015).

Concomitant with the strong warming observed in the North Sea, demersal fish stocks have undergone a variety of changes that have important consequences for the productivity of Scottish fisheries. It has been suggested that spatial distribution of fish in the North Sea has shifted northwards or deepened (Perry et al. 2005; Rindorf and Lewy 2006; Engelhard et al. 2014), however, these responses are not consistently observed across the North Sea fish community (see Dulvy et al. 2008 and results therein). Thus, the exact cause of the distributional response is somewhat uncertain. At the same time, several commercially important fish stocks have exhibited a synchronous trend towards smaller maximum body sizes (Baudron et al. 2014), an expected response according to the physiologically-based temperature-size rule (i.e., organisms that develop under higher temperatures attain smaller body sizes; Atkinson 1994). Lastly, both cod and sole in the North Sea are spawning earlier (Fincham et al. 2013, McQueen and Marshall 2017) which is consistent with our physiological understanding of temperature impacts on rates of gonadal development (Kjesbu et al. 2010). Earlier spawning could have important implications for recruitment rates of commercial stocks (Mullowney et al 2016; Regnier et al. 2017).

There are a wide range of direct impacts of climate change on fisheries. Changing spatial distribution has profound impacts on the regional distribution of catching opportunities and consequently the degree of match, or mis-match, between available quota and catch. In Europe this issue has come into particular focus given that national shares of quotas were fixed based on data for a much earlier time period (1971-1976); these fixed shares (termed “relative stability”) are increasingly maladapted to current and future distributions of fish (Section 3.2). Climate-mediated changes in individual growth rates, as indicated by declines in maximum body size, can affect fisheries economics (smaller fish are less valuable) and decrease yields (Section 4.2.1). Fishing mortality reference points are also likely be affected by changes in size at age, calling into question the effectiveness of current management strategies which use fixed reference points that do not correspond to current and future conditions. The behaviour of individual harvesters can also be affected by fish size, which interacts with other factors such as travel costs, spatial management measures, season, and regulatory framework (Haynie and Pfeiffer 2012). More fundamentally, individual growth rates, which determine maximum body size, are an important component of population resilience owing to the relevance of individual growth rates and adult body size for reproduction (Vasilakopoulos and Marshall 2015). The loss of resilience that is caused by a shift towards smaller-sized fish make populations unstable and more vulnerable to abrupt, discontinuous state shifts which are termed critical transitions (Scheffer et al. 2009). Continued warming could potentially lead to a loss of resilience to stressors, including fishing, particularly if it causes further decreases in maximum body size.

Owing to the economic importance of the topic, there have been previous syntheses that are relevant to this project. A recent report by the FAO considered climate change impacts on wild capture fish and aquaculture on a global scale (Barange et al. 2018). It was written primarily for policymakers, fisheries managers and practitioners, with a view to assisting countries in delivery of mitigation and adaptation obligations (http://www.fao.org/3/i9705en/i9705en.pdf). Different regions were summarised by individual chapters authored by regional experts. Chapter 5 of the FAO report considered climate change impacts, vulnerabilities and adaptations for the North Atlantic and Atlantic marine fisheries. It was co-authored by two workshop participants (M. Peck and J. Pinnegar).

1.2 Industry perception of climate change

Climate change, which occurs slowly over long-term time scales, is rarely a high priority for the fishing industry which is primarily focused on addressing short-term issues. Nevertheless, climate change has already impacted fisheries in underappreciated ways. Climate change has already created a "shifting baselines" problem that is apparent in the changing spatial distribution of mackerel disrupting international quota allocation (Jansen et al., 2016; Nøttestad et al., 2015) and shrinking body sizes which have decreased yields of several North Sea fish stocks when expressed on a per recruit basis (Baudron et al. 2014; Olafsdottir et al., 2016). There have been changes in the severity and frequency of extreme weather events that have direct influences on fishing operations (Sainsbury et al 2018). Recently, a global analysis of productivity of 235 populations of 124 species suggests that the maximum sustainable yields decreased by 4.1% overall from 1930 to 2010 (Free et al 2019) which the study partly attributes to warming. The greatest losses of productivity have occurred in the Sea of Japan, North Sea, Iberian Coast, Kuroshio Current and Celtic-Biscay Shelf ecoregions which have all undergone warming (Belkin 2009). Clearly, impacts have already taken place that, in aggregate, are not understood by the fishing industry or recognised by fisheries managers. This highlights a need to communicate the current state of knowledge in clear and accessible formats that customised to specific sectors, e.g., pelagic, demersal or shellfish fleets.

1.3 Impacts of climate change on fisheries policy and vulnerability

Like most modern fisheries, Scotland's fisheries are currently managed using the principle of Maximum Sustainable Yield (MSY). Given that the availability and productivity of fish stocks can both be influenced by climate change (Sections 3 and 4), future adjustments to MSY and quota allocations may be necessary. There is currently no mechanism for adjusting advice based on impacts of climate change on MSY. Similarly, there is little fisheries legislation at the Scottish level that references climate change explicitly or stipulates specific actions for managing or mitigating its impacts.

Vulnerability is the propensity or predisposition to be adversely affected. The vulnerability of fisheries to climate change has been evaluated at a global scale (Allison et al 2009; Blasiak et al. 2017; Ding et al. 2017). These global assessments of vulnerability found UK fisheries to have low vulnerability relative to other global fisheries. These comparatively positive assessments did not distinguish between Scottish and other UK fisheries. The Department for Environment, Food and Rural Affairs (Defra) has undertaken a comparatively detailed analysis of vulnerability in the sense of identifying risks. For example, two national Climate Change Risk Assessments (CCRAs), undertaken in 2012 and 2017 (Section 5.2.1), provide a technical assessment of climate change risks to the fishing industry. Although relatively limited in scope, they highlight the need for an increased understanding of how climate change will impact fisheries and fishing communities.

1.4 Adapting to climate change

The ability of the fishing industry to adapt to climate change depends on its adaptive capacity (Bennett et al. 2014; Stoll et al. 2014). Adaptive capacity is the ability of systems, institutions, and humans to adjust to potential damage, to take advantage of opportunities, or to respond to the consequences of change. Fishers may not recognise a need for adaptation because they do not view climate change as a salient issue, have low risk perceptions of climate change or are sceptical of its impacts (Nursey-Bray et al 2012; Dannevig and Hovesrud 2016). A recent study of a small group of fishers in a UK fishing port (Brixham) indicated that fishers were aware of how climate change could impact their fisheries, however many fishers did not anticipate having to change their practices (Maltby 2018). Reasons given for not changing current practices include not wanting to change as well as constraints that affected their ability to change such as inflexible management and lack of finances.

A recent Seafish report (Garrett et al 2016) consulted seafood industry stakeholders to identify adaptation responses that the industry could adopt to prepare for future climate change (Section

5.2.3). These included reviewing quota allocation in relation to “relative stability”, improving safety of crew and vessels, developing the evidence base for climate impacts of fisheries, and improving relationships between science and industry to promote knowledge exchange. Any consideration of implications of climate change for fishing needs to consider identifying adaptation responses that would address the possible impacts of climate change.

1.5 Aims of the FIS028

As noted above, this project was based on the premise that reviewing the empirical evidence describing temperature impacts on the spatial distribution and growth of fish over broad spatial scales is the necessary precursor to developing statistical models that are capable of robustly forecasting the impacts of climate change on the resilience of commercial fish stocks. Having some degree of forecasting ability would benefit the fishing industry by providing an informed view of future operating conditions and help to shape effective policy tools for fisheries management.

Developing a well-founded forecasting model requires synthesising current knowledge, identify knowledge gaps and plan follow-up research programmes. This phased approach is fully consistent with the request by FIS for the workshop “*explore the current state of knowledge related to climate change impacts on fish distribution and to identify developments for the future*”.

FIS also specified that, although the primary focus was on climate change and its implications for Scottish fisheries, the workshop should also consider broader topic of innovation in the use of fish distribution data. Adding fish growth to this review was a complementary and unique feature of our project. Individual growth contributes biomass production and therefore determines per capita yields of fisheries. Growth and distribution are also linked given that the thermal experience of a fish is determined by its location in space. If a fish stock’s distribution is unchanged by climate change then the stock’s thermal experience will be different and likely warmer. This will have long-term consequences for individual growth and therefore yields.

Additionally, the workshop undertook a brief review of the approaches taken by the three focal countries (Australia, UK, and US) towards adaptation planning within the fishing industry. This is an area with significant scope for innovation, informed by the range of international perspectives on adaptation. It therefore is relevant to developments for the future.

The workshop addressed three separate questions, each associated with written outcomes in the form of manuscripts being planned for future:

1) *Are there common patterns in the type of distributional responses being observed in different regional seas that are based on the degree and direction of temperature changes in those regions and/or attributes of the individual species*?

> **Manuscript**: Worldwide review of empirical evidence of changes in distribution and their causes (*completed after the workshop through coordinated efforts by participants*).

2) *Is there a common response in fish growth rates to increasing water temperatures consistent with physiological knowledge*?

> **Manuscript**: Worldwide review of empirical evidence of changes in growth and their causes (*completed after the workshop through coordinated efforts by participants*);

> **Manuscript**: Meta-analysis of the historical changes in fish growth across the globe and identification of putative mechanisms e.g., the temperature-size rule (*completed after the workshop through coordinated research efforts by participants*).

3) *What are the implications for Scottish fisheries, including knowledge gaps*?

> **Final project report**: On the basis of discussions held at both the workshop and the public event the implications for Scottish fisheries will be identified and key knowledge gaps will be identified to inform FIS of future research needs. For example, climate change also affects fishery economics, management, and fleet dynamics will be discussed at the workshop in order to identify future research needs in these areas (*the FIS028 final report will outline working arrangements for delivering Manuscripts specified above*).

In addition, a public event was held at the University of Aberdeen on Wednesday 28th November 2018 to share global and local perspectives on the importance of climate change for distribution, productivity and management of commercial fish stocks. Speakers from the UK, USA and Australia presented state-of-the-art scientific findings followed by presentations by members of the Scottish fishing industry (Section 2.2). A Q&A session followed allowing members of the audience to question the speakers about what the future holds for our marine fish, fishing industries and coastal communities.

2 Organisation of FIS028

The generous level of funding made available by FIS was well suited to assembling an international consortium of experts to review and summarise knowledge from different areas.

2.1 Organisation of the workshop

Workshop attendees were invited to the workshop by the co-organisers (C.T. Marshall, P. Spencer) because they had expert knowledge in the topics of fish growth and distribution and/or having access to relevant government databases. Several attendees were invited because of having suitable expertise in modelling of fish growth or distribution. Other attendees were invited on the basis of having either national or international perspectives on climate change impacts on fish and fisheries. There were a total of 19 attendees including the two co-organisers (Table 1). The international representation of the working group is highlighted by the diverse range of countries represented, including the UK, Australia, US, Canada, Norway, Iceland, Denmark, and Germany. Attendees included a mix of government scientists, university-based scientists, and one industry scientist from the Scottish Pelagic Fishermen's Association.

During the 5-day workshop the working group tackled the three questions (see Section 1.5) through a mix of presentations, plenary discussions and break-out group discussions. In addition, eight scientists, representing US, Canada, Australia, and Chile, gave presentations remotely and participated in discussions *(*Table 1). The timetable was divided into two topics: distribution (Monday and Tuesday) and growth (Tuesday, Wednesday, Thursday). Discussions reviewed data availability (Monday afternoon, Thursday morning) and considered the most appropriate analytical methods for analysing the existing distribution data (Tuesday afternoon) and growth data (Wednesday morning, Thursday afternoon) available for the different regions. Towards the close of the workshop, discussions focussed on developing a plan for future collaborative research (Thursday afternoon, Friday afternoon).

Role	Names (Affiliation)
Workshop organisers	Tara Marshall (University of Aberdeen, UK) Paul Spencer (NOAA Fisheries, Alaska Fisheries Science Center, US) Alan Baudron (University of Aberdeen, UK) Niall Fallon (University of Aberdeen, UK)
Workshop attendees	Paul Fernandes (University of Aberdeen, UK) Thomas Helser (NOAA Fisheries, Alaska Fisheries Science Center, US) Melissa Haltuch (NOAA Fisheries, Northwest Fisheries Science Center, US) Christine Stawitz (NOAA, Office of Science and Technology, US) Bjarte Bogstad (Institute of Marine Research, Norway) Einar Hjörleifsson (Marine Research Institute, Iceland) Alan Haynie (NOAA Fisheries, Alaska Fisheries Science Center, US) Robert Allman (NOAA, Southeast Fisheries Science Center, US) Gretta Pecl (University of Tasmania, Australia) John Pinnegar (Centre for Environment, Fisheries and Aquaculture Science, UK) Pieter Daniël van Denderen (National Institute of Aquatic Resources, Technical University of Denmark, Denmark) Bryony Townhill (Centre for Environment, Fisheries and Aquaculture Science, UK) Joanna Bernhardt (University of British Columbia, Canada) Myron Peck (University of Hamburg, Germany) Steve Mackinson (Scottish Pelagic Fishermen's Association, UK)
Remote participants	Malin Pinsky (Rutgers University, USA) William Cheung (University of British Columbia, Canada) James Thorson (NOAA Fisheries, Alaska Fisheries Science Center, US) Asta Audzijonyte (University of Tasmania, Australia) John Morrongiello (University of Melbourne, Australia) Curtis Champion (University of Tasmania, Australia) Tim Essington (University of Washington, USA) Tim Miller (NOAA, Northeast Fisheries Science Center) Rodrigo Wiff (Fisheries Development Institute, Chile)

Table 1: Workshop participants and their affiliations

2.2 Organisation of the public event

The public event was titled: *Climate impacts on fish distribution and productivity and implications for Scottish fisheries - How could climate change affect marine fish and fisheries?* It was held Wednesday 28th November, Main Lecture Theatre, Zoology Building. University of Aberdeen. Over 100 people attended the event, including representatives from FIS, Seafish, Scottish Fishermen's Federation and Marine Scotland. There were five speakers:

Prof. Gretta Pecl – University of Tasmania, Australia

Dr. John Pinnegar – Centre for Environment, Fisheries and Aquaculture Science, UK

Dr. Alan Haynie – Alaska Fisheries Science Center, USA

Mr. George R West – skipper of the pelagic trawler *Resolute*

Dr. Steven Mackinson – Scottish Pelagic Fishermen's Association

Each speaker gave a short 15-minute presentation followed by Q&A session followed by a reception in the foyer allowing further informal discussions about climate change and fish. The funding from FIS was acknowledged and the FIS logo appeared prominently.

To enhance the reach of the public event using social media, FIS028 secured the participation of Mindfully Wired Communications (MWC)[1]. MWC prepared visually appealing poster, flyer and mailshot which were disseminated to promote the public event. MWC enabled interested persons to engage with FIS's own social media through Facebook, Twitter and the FIS website. A review of the event's Twitter handle (#FISClimateImpacts) showed that MWC had posted 40 tweets over the full week and 13 live tweets during the public event itself. Externally 23 people used the hashtag and the hashtag was seen by a minimum of 19,589 accounts. There were 570 engagements with the tweets including 90 likes, 205 retweets, 82 link clicks, and 32 hashtag clicks.

2.3 Live-streaming and recording of the workshop and public event

Considerable effort was made to increase wider engagement with the workshop through the use of online digital media. Live-streaming and recording of key talks and events over the course of the workshop was identified as an excellent means of facilitating remote engagement with workshop content, while also providing a legacy package for the workshop. This was achieved by facilitating the presentation of material, allowing remote participants to engage with group discussions, and by providing a means for interested members of the public to follow the proceedings of the workshop in real-time. MWC advertised the live-streaming opportunity via social media. The Panopto software package[2] was used to capture audio of speakers' talks, as well as PowerPoint presentations, during streaming and recording. In advance of the workshop, a timetable was circulated to remote participants and other interested colleagues containing hyperlinks pointing to web locations from which a selection of talks would be live-streamed. Preparing the live-stream links in advance meant each talk was ready to be recorded to a specific location as the workshop proceeded, allowing for minimal technical intervention from the organisers. As the hyperlinks were accessible to anyone possessing them, permission was sought from speakers before proceeding with the streaming and recording. The videos (powerpoints with audio) are all viewable through a standard internet browser, and have been archived offline as it is proposed that they will be shared via another online platform in future (Section 8.4). As well as the majority of workshop talks, the public event "*Climate impacts on fish distribution and productivity: implications for Scottish fisheries*" was streamed and recorded in its entirety using Panopto. This included presentations from the five invited speakers, as well as the public questions and answers session which followed. The videos are currently hosted online[3], and have been viewed 239 times as of 2 April 2019. The powerpoints and audio from public event are also stored digitally.

---

[1] this was not a part of the original proposal but was recognised as appropriate particularly given increased public interest in climate change that followed the publication of the IPCC report

[2] https://www.panopto.com/

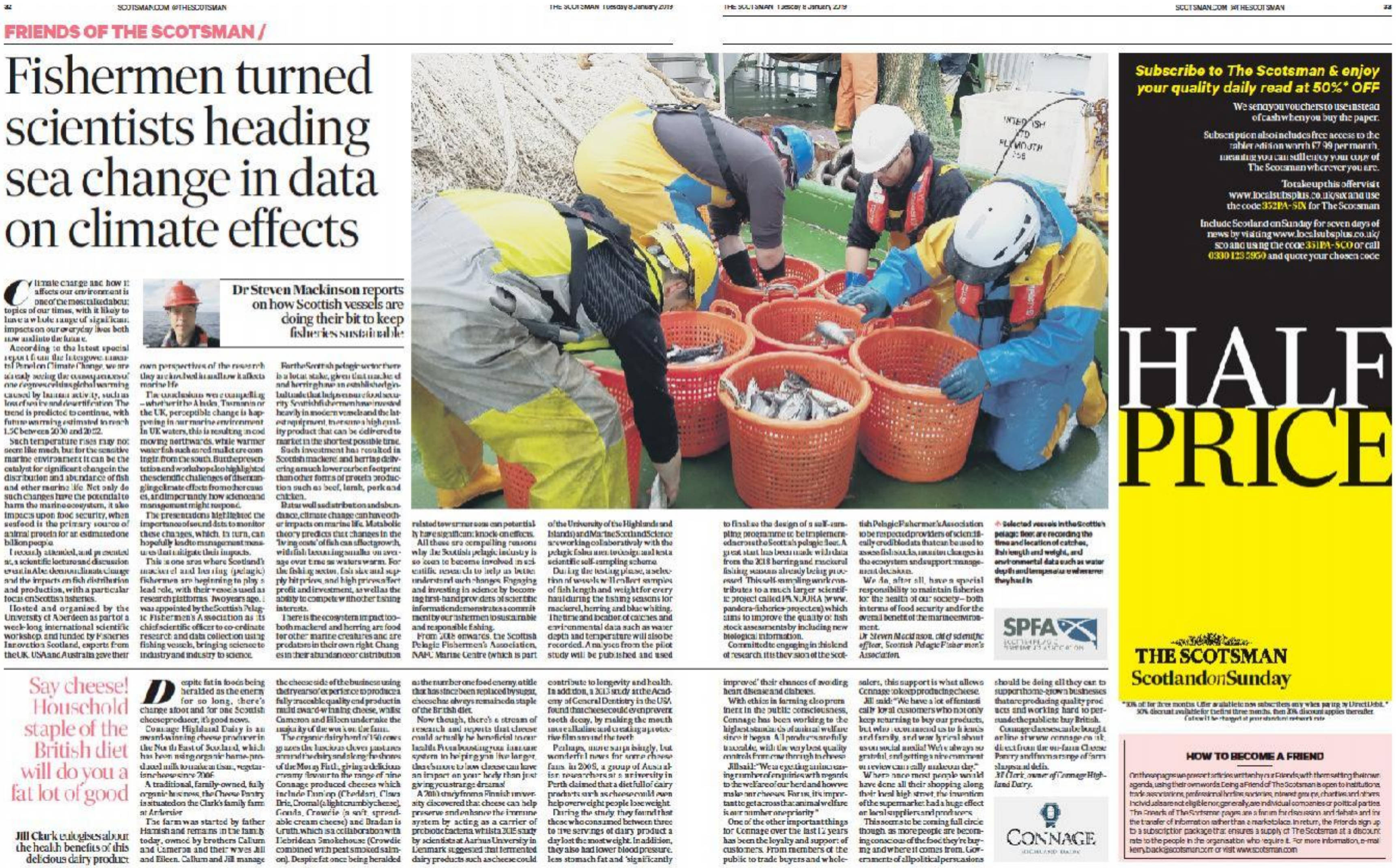
[3] https://abdn.cloud.panopto.eu/Panopto/Pages/Sessions/List.aspx#folderID=%22b8e8dc40-6430-4c13-9c5a-a99f00edd183%22&sortColumn=0&sortAscending=true

2.4 Print media

A news release was prepared and disseminated by MWC as well as the University of Aberdeen Communications team. As a result, there were several articles about the public event in the print media including the following:

Scotsman: appeared 8 January 2019 (Figure 1)
Fisker Forum: appeared 14 December 2018; has a EU-wide outreach, and a particularly strong readership in Sweden and Denmark http://www.fiskerforum.dk/en/news/b/what-climate-change-could-mean-for-scottish-fisheries
Fishing News: appeared 13 December 2018 (Figure 2)
Seafish: appeared 10 December 2019 in the Marine Environment Newsletter sent by E. Pinn.
Though the Gaps: appeared 4 December 2018; southwest-focused blog for industry, reaching an audience of over 11,000 http://blog.through-the-gaps.co.uk/2018/12/a-new-climate-for-fishing.html

The FIS support for research on climate change appeared prominently in all of these articles.



32 SCOTSMAN.COM @THESCOTSMAN THE SCOTSMAN Tuesday 8 January 2019

THE SCOTSMAN Tuesday 8 January 2019 SCOTSMAN.COM @THESCOTSMAN 33

FRIENDS OF THE SCOTSMAN /

Fishermen turned scientists heading sea change in data on climate effects

Dr Steven Mackinson reports on how Scottish vessels are doing their bit to keep fisheries sustainable

Climate change and how it affects our environment is one of the most talked about topics of our times, with it likely to have a whole range of significant impacts on our everyday lives both now and into the future.

According to the latest special report from the Intergovernmental Panel on Climate Change, we are already seeing the consequences of one degree celsius global warming caused by human activity, such as loss of sea ice and desertification. The trend is predicted to continue, with future warming estimated to reach 1.5C between 2030 and 2052.

Such temperature rises may not seem like much, but for the sensitive marine environment it can be the catalyst for significant change in the distribution and abundance of fish and other marine life. Not only do such changes have the potential to harm the marine ecosystem, it also impacts upon food security, when seafood is the primary source of animal protein for an estimated one billion people.

I recently attended, and presented at, a scientific lecture and discussion event in Aberdeen on climate change and the impacts on fish distribution and production, with a particular focus on Scottish fisheries.

Hosted and organised by the University of Aberdeen as part of a week-long international scientific workshop, and funded by Fisheries Innovation Scotland, experts from the UK, USA and Australia gave their own perspectives of the research they are involved in and how it affects marine life.

The conclusions were compelling – whether it be Alaska, Tasmania or the UK, perceptible change is happening in our marine environment. In UK waters, this is resulting in cod moving northwards, while warmer water fish such as red mullet are coming in from the south. But the presentation and workshop also highlighted the scientific challenges of disentangling climate effects from other causes, and importantly, how science and management might respond.

The presentations highlighted the importance of sound data to monitor these changes, which, in turn, can hopefully lead to management measures that mitigate their impacts.

This is one area where Scotland's mackerel and herring (pelagic) fishermen are beginning to play a lead role, with their vessels used as research platforms. Two years ago, I was appointed by the Scottish Pelagic Fishermen's Association as its chief scientific officer to co-ordinate research and data collection using fishing vessels, bringing science to industry and industry to science.

For the Scottish pelagic sector there is a lot at stake, given that mackerel and herring have an established global trade that helps ensure food security. Scottish fishermen have invested heavily in modern vessels and the latest equipment, to ensure a high quality product that can be delivered to market in the shortest possible time.

Such investment has resulted in Scottish mackerel and herring delivering a much lower carbon footprint than other forms of protein production such as beef, lamb, pork and chicken.

But as well as distribution and abundance, climate change can have other impacts on marine life. Metabolic theory predicts that changes in the 'living costs' of fish can affect growth, with fish becoming smaller on average over time as waters warm. For the fishing sector, fish size and supply hit prices, and high prices affect profit and investment, as well as the ability to compete with other fishing interests.

There is the ecosystem impact too – both mackerel and herring are food for other marine creatures and are predators in their own right. Changes in their abundance or distribution related to warmer seas can potentially have significant knock-on effects.

All these are compelling reasons why the Scottish pelagic industry is so keen to become involved in scientific research to help us better understand such changes. Engaging and investing in science by becoming first-hand providers of scientific information demonstrates a commitment by our fishermen to sustainable and responsible fishing.

From 2018 onwards, the Scottish Pelagic Fishermen's Association, NAFC Marine Centre (which is part of the University of the Highlands and Islands) and Marine Scotland Science are working collaboratively with the pelagic fishermen to design and test a scientific self-sampling scheme.

During the testing phase, a selection of vessels will collect samples of fish length and weight for every haul during the fishing seasons for mackerel, herring and blue whiting. The time and location of catches and environmental data such as water depth and temperature will also be recorded. Analyses from the pilot study will be published and used to finalise the design of a self-sampling programme to be implemented across the Scottish pelagic fleet. A great start has been made with data from the 2018 herring and mackerel fishing seasons already being processed. This self-sampling work contributes to a much larger scientific project called PANDORA (www.pandora-fisheries-project.eu) which aims to improve the quality of fish stock assessments by including new biological information.

Committed to engaging in this kind of research, it is the vision of the Scottish Pelagic Fishermen's Association to be respected providers of scientifically credible data that can be used to assess fish stocks, monitor changes in the ecosystem and support management decisions.

We do, after all, have a special responsibility to maintain fisheries for the health of our society – both in terms of food security and for the overall benefit of the marine environment.

Dr Steven Mackinson, chief scientific officer, Scottish Pelagic Fishermen's Association.

Selected vessels in the Scottish pelagic fleet are recording the time and location of catches, fish length and weight, and environmental data such as water depth and temperature wherever they haul in

Say cheese! Household staple of the British diet will do you a fat lot of good

Jill Clark eulogises about the health benefits of this delicious dairy product

Despite fat in foods being heralded as the enemy for so long, there's change afoot and for one Scottish cheese producer, it's good news.

Connage Highland Dairy is an award-winning cheese producer in the North East of Scotland, which has been using organic home-produced milk to make artisan, vegetarian cheese since 2006.

A traditional, family-owned, fully organic business, the Cheese Pantry is situated on the Clark's family farm at Ardersier.

The farm was started by father Hamish and remains in the family today, owned by brothers Callum and Cameron and their wives Jill and Eileen. Callum and Jill manage the cheese side of the business using their years of experience to produce a fully traceable quality end product in multi award-winning cheese, whilst Cameron and Eileen undertake the majority of the work on the farm.

The organic dairy herd of 150 cows grazes the luscious clover pastures around the dairy and along the shores of the Moray Firth, giving a delicious creamy flavour to the range of nine Connage produced cheeses which include Dunlop (Cheddar), Clava Brie, Cromal (a light crumbly cheese), Gouda, Crowdie (a soft, spreadable cream cheese) and Bradan is Gruth, which is a collaboration with Hebridean Smokehouse (Crowdie combined with peat smoked salmon). Despite fat once being heralded as the number one food enemy, a title that has since been replaced by sugar, cheese has always remained a staple of the British diet.

Now though, there's a stream of research and reports that cheese could actually be beneficial to our health. From boosting your immune system to helping you live longer, there's more to how cheese can have an impact on your body than just giving you strange dreams!

A 2010 study from a Finnish university discovered that cheese can help preserve and enhance the immune system by acting as a carrier of probiotic bacteria whilst a 2015 study by scientists at Aarhus University in Denmark suggested that fermented dairy products such as cheese could contribute to longevity and health. In addition, a 2013 study at the Academy of General Dentistry in the USA found that cheese could even prevent tooth decay, by making the mouth more alkaline and creating a protective film around the teeth.

Perhaps, more surprisingly, but wonderful news for some cheese fans, in 2008, a group of Australian researchers at a university in Perth claimed that a diet full of dairy products such as cheese could even help overweight people lose weight.

During the study, they found that those who consumed between three to five servings of dairy product a day lost the most weight. In addition, they also had lower blood pressure, less stomach fat and 'significantly improved' their chances of avoiding heart disease and diabetes.

With ethics in farming also prominent in the public consciousness, Connage has been working to the highest standards of animal welfare since it began. All products are fully traceable, with the very best quality controls from cow through to cheese.

Jill said: "We are getting an increasing number of enquiries with regards to the welfare of our herd and how we make our cheeses. For us, it's important to get across that animal welfare is our number one priority."

One of the other important things for Connage over the last 12 years has been the loyalty and support of customers. From members of the public to trade buyers and wholesalers, this support is what allows Connage to keep producing cheese.

Jill said: "We have a lot of fantastically loyal customers who not only keep returning to buy our products, but who recommend us to friends and family, and wax lyrical about us on social media! We're always so grateful, and getting a nice comment or review can really make our day."

Where once most people would have done all their shopping along their local high street, the invention of the supermarket had a huge effect on local suppliers and producers.

This seems to be coming full circle though, as more people are becoming conscious of the food they're buying and where it comes from. Governments of all political persuasions should be doing all they can to support home-grown businesses that are producing quality products and working hard to persuade the public to buy British.

Connage cheeses can be bought online at www.connage.co.uk, direct from the on-farm Cheese Pantry and from a range of farm shops and delis.

Jill Clark, owner of Connage Highland Dairy.

HOW TO BECOME A FRIEND

On these pages we present articles written by our Friends, with them setting their own agenda, using their own words. Being a Friend of The Scotsman is open to institutions, trade associations, professional bodies, societies, interest groups, charities and others. Individuals are not eligible nor, generally, are individual companies or political parties. The Friends of The Scotsman pages are a forum for discussion and debate and for the transfer of information rather than a marketplace. In return, the Friends sign up to a subscription package that ensures a supply of The Scotsman at a discount rate to the people in the organisation who require it. For more information, e-mail kerry.black@scotsman.com or visit www.scotsman.com

Figure 1. Newspaper article from Scotsman published 8 January 2019

A new climate for fishing

Over 100 guests gathered at a public event on Wednesday, 28 November to find out more about what climate change could mean for Scottish fisheries.

Part of an international five-day workshop on climate change hosted by the University of Aberdeen, and funded by Fisheries Innovation Scotland (FIS), the public event brought together students, scientists, and fishing industry and government representatives, alongside interested locals, to offer an open forum for questions and discussion.

The hot topic was: will changes in ocean temperatures drive a sea-change in marine fisheries? And if so, what will it mean for businesses and livelihoods that depend on them?

An expert panel featured world-renowned climate change scientists including Gretta Pecl from the University of Tasmania, fisheries economist Alan Haynie from Alaska Fisheries Science Centre, and Gardenstown pelagic skipper George West (Resolute BF 70).

Commenting on the range of expertise in the room, FIS executive director Kara Brydson said: "FIS is a unique charity which supports collaboration and knowledge exchange between fishers, scientists, government and the seafood supply chain. We commission research and events that not only raise awareness of issues that could impact on profitable and sustainable fisheries, but also find innovative ways to combat these problems, thanks to partnerships between scientists and the Scottish fishing industry."

Among the key messages from the day's presentations was the need for an 'all hands on deck' approach to respond quickly to the 'massive' changes that climate change will bring to fisheries. John Pinnegar of the Marine Climate Change Centre highlighted how valuable species are moving north, looking for cooler waters. He predicted that Scottish fishing staples like cod and herring would be 'losers' under climate change, struggling with shifts in sea conditions. Species that thrive in warmer waters, including squid, sprat and sea bass, are predicted to benefit.

A presentation from the Scottish Pelagic Fishermen's Association by scientist Steven Mackinson shone a light on the role of the fishing industry as data-gatherers. An FIS-funded initiative is supporting efforts to improve the stock assessment for herring through genetic sampling onboard pelagic vessels. The audience heard how a clear picture of stock status now, and in the future, will help to anticipate and adapt to the challenges of a changing climate.

Skipper George West shared a fisherman's perspective by outlining changes he has seen over four decades at sea, including the 'unexpected' southward shift of mackerel. He detailed how the pelagic industry is already doing a lot to protect the fishery from a warming climate, with investment in more fuel-efficient vessels that can travel further following shifting stocks, and stronger collaborations with climate change scientists.

After the event, participants were encouraged to join a reception where they could ask visiting scientists and industry representatives questions about climate change and fish. An attendee from Marine Scotland was glad to see a mixture of industry representatives, economists and scientists given an opportunity to speak at a scientific event, saying: "This event felt really inclusive, which makes it much more worthwhile."

"The combination of speakers benefits our interpretation of past climate changes, and also allows us to make more robust predictions about future impacts," said event lead Dr Tara Marshall, senior lecturer in fisheries science at Aberdeen University.

"The compelling presentations given at the public event will be made available on the FIS website (**fiscot.org**), along with ideas on how the research community and industry in Scotland can continue to work together to investigate and prepare for climate change."

Figure 2. Article covering the workshop and public event, published in Fishing News, 13th December 2018.

2.5 Organisation of this report

Section 3 and 4 of this report summarises the information that was presented on the topics of distribution and growth, respectively. Each section reviews the evidence of climate change (distributional shifts and changes in individual growth rates) for fish in Australia, the UK and US. Both sections include a summary of the different modelling approaches that are being used for these two topics (Sections 3.3 and 4.4). Additionally, management implications of distributional shifts in European Union (EU) waters (including zonal attachment) and changes in individual growth rate are presented in Sections 3.2 and 4.2, respectively. Section 4 also includes a review of databases available to modelling growth. Section 5 gives a summary of the approaches to adaptation planning taken in Australia, UK and US and concludes with a comparison of the three approaches. Sections 6 summarises insights that were gained during the workshop that are applicable to the global situation while Section 7 identifies knowledge gaps specific to Scottish fisheries. Both Sections 6 and 8 were written to inform FIS of options for commissioning future work. The report concludes with a description of the scientific legacy of the workshop (Section 8).

The objectives of this workshop dovetail closely with several ongoing, large research programs within the EU (Horizon 2020) and elsewhere. One project, titled the Climate Change and European Aquatic Resources project (CERES; www.ceresproject.eu), is completing its third of four years and a brief summary of CERES was presented at the workshop. A brief summary of that project is included (Appendix 1, Section 11.1).

3 Climate change impacts on fish distribution

Globally, there have been several published studies investigating distribution of marine species either a whole range of taxa or species in specific regions. Across those studies between 25 and 85% of species have shown evidence of shifting (Figure 3). Variation in the timing and pace of distributional shifts occurs because there are influences other than climate, issues with detectability, and(or) not all species shift with some species either adapting or dying out. Some of the variation in rate and magnitude of changes in distribution can be explained by climate velocity, which refers to the movement of temperature isotherm in space (Molinos et al. 2017). Climate velocity combined with species traits explains even more of this variation (Sunday et al 2015). Additionally, widely distributed species and species at lower trophic levels are shifting faster (Sunday et al. 2015). However, some of the variation in rate and magnitude of range shifts can be attributed to the methods used to detect and quantify the shifts (Brown et al. 2016).

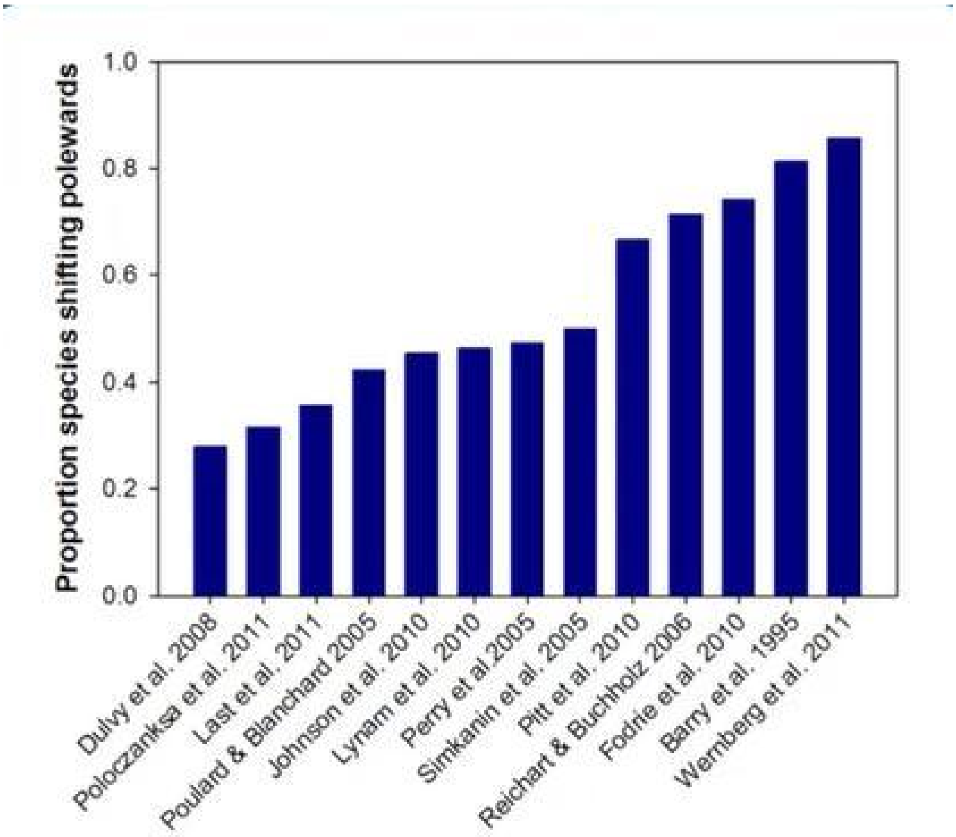


Figure 3. Published studies of marine distributional shifts indicating the proportion of species which were judged by the study to have shifted polewards consistent with expected response to warming. Figure from presentation given at the workshop by G. Pecl.

Arrival in a new area occurs in stages with the starting point being absence in the new area (pre-warming), followed by arrival in the new area (response to mild warming) then population increases and then persistence (Bates et al. 2014). The receptiveness of the receiving community is also important and may possibly be determined by the existing ecological network in the new area and its stability or instability. A range shift is therefore a function of two separate aspects: how predisposed a given species is to shifting and the receptiveness of the new ecosystem and habitat to the incoming species.

3.1 Review of climate impacts on spatial distribution

3.1.1 Australia

The east coast of Tasmania produces the highest value of seafood nationally, and a high rate of recreational fishing. It is also one of the fastest warming regions globally with the east coast of Tasmania warming faster than 90% of the ocean, i.e., in the top 10% for rates of Sea Surface Temperature (SST) warming. Consequently, a substantial research investment has been made in understanding climate change impacts, particularly changes in species distribution. Changes in species distribution that have been detected include poleward expansions of sea urchins resulting in a loss of kelp forests (Ling et al. 2009a), the invasion of new octopus species (Ramos et al. 2018), poleward expansion of 50% of intertidal species over the last 50 years (Pitt et al. 2010), distributional changes of many fish species (Last et al. 2011, Sunday et al. 2015, Robinson et al. 2015, Day et al. 2018) and a foundational shift of seaweed communities poleward (Wernberg et al. 2011). Marine ecosystems off the east coast of Tasmania today are profoundly different from two decades ago (Pecl et al in press).

The ecological consequences of distributional shifts of single species can be large. For example, the climate-driven extension of urchins has had the same ecological impact as an invasive species, depleting kelp beds and leading to rocky urchin barrens (Ling et al. 2009a). Large lobsters can eat the urchins but are removed through fishing (Robinson et al 2019), however the role of other shifting and potentially interacting species is unexplored. For example the range-extending gloomy octopus could be reinforcing the negative impact of the urchin because it eats larger lobsters (Marzloff et al. 2016). This illustrates how distributional shifts for a single species can have knock-on consequences on ecosystem functioning and how multiple species shifts may need to be considered together.

In Australian waters more there are spatial differences in the degree to which shifts in distributions (either expansion or contraction) are observed (Gervais, Pecl et al in prep). As noted above, Tasmania is the main hotspot of range shift observations with poleward range expansions observed in 88% of the species recorded as undergoing changes in distributions. In eastern Australian waters, although many species are still documented as range extending, 23% of species have also shown range contractions. In western Australia mostly range expansions are most frequently observed. Most of the species shifting are temperate species. Overall, Australia is a data poor region in the sense of lacking long-term standardised research survey data. A range of alternative data sources are therefore used to describe spatial distribution of fish including citizen science initiatives, use of baseline data for historic surveys, and commercial catch data.

The implications of range shifts and other climate change impacts for fisheries in Australia have been investigated and potential adaptation options explored (Pecl et al 2014). Further poleward shifts are expected (Champion et al 2018b), and warmer water may also influence seasonality, i.e., timing of events including breeding/spawning, migrations, ontogenetic changes (Munday et al. 2008). Changes in distribution of some large mobile species predator species are also expected e.g. Tiger sharks (Payne et al. 2018) and crocodiles.

3.1.2 UK & Europe

There have been many examples of fish distribution shifts in Europe occurring in the past century. These have been particularly well documented in the North Sea, Norwegian Sea and Barents Sea. In UK waters, studies have been able to make use of data held by the Centre for Environment, Fisheries and Aquaculture Science (Cefas) which was established as a fisheries laboratory back in 1902. Since then, Cefas has been monitoring where, when and how much fish are landed in UK ports. Cefas also holds a spatial time series of commercial catch per unit effort data from 1913, and over 37,000 statistical charts have been recently digitised.

Over this 100-year time scale, there has been changes in the North Sea where warm water species, having smaller body sizes, have increased in abundance (Simpson et al., 2011). Through the 20th century, there used to be mass mortalities of common sole in the North Sea when winter temperatures dropped (Woodhead, 1964). Sole avoided the shallow coastal areas in cold winters, and instead concentrated in the deeper waters in the central North Sea. In more recent years, as the winters have been warmer, sole have retreated towards the English Channel and are able to stay in shallow waters all year (Engelhard et al., 2011). The distribution of plaice has also changed in the past century. In the 20th century they were constrained to the south east North Sea, but have recently shifted towards the Dogger Bank and the north-west North Sea, going into deeper waters (Engelhard et al., 2011). Turbot, which was formerly distributed widely throughout the North Sea, has almost disappeared from the north east since the 1960s (Kerby et al., 2013). In this case, they may have been heavily depleted by fishing, rather than climate change. Two lesser known species, the solenette (*Buglossidium luteum*) and scaldfish (*Arnoglossus laterna*), have increased in abundance and moved north since the 1980s, coinciding with mild winters (van Hal et al., 2010). After a cold winter in 1996, their abundance decreased and they retracted southwards. More recent temperature changes then allowed them to increase in abundance again.

There have also been complex interactions between temperature and fishing which determine fish population dynamics and consequently spatial distributions. For example, Atlantic cod (*Gadus morhua*) was overfished in the early-mid 2000s. As a result, fishing mortality was significantly reduced and the stock biomass increased, but the recovery has been slow. This could be due to long-term poor recruitment because the warmer winters since the mid-1990s don't favour successful cod reproduction. Seabass expanded around the UK in the early 2000s, and this was initially thought to be related to temperature. However, fishing mortality was high which negatively impacted recruitment and a number of colder winters in the late 2000s has caused the stock to decline again. Squid distribution has been studied using Cefas trawl surveys from 1980 to 2014 (van der Kooij et al., 2016). Summer fisheries for squid have expanded rapidly in the Moray Firth, where fishers are able to catch squid where they have restrictions on more traditional finfish species managed with Total Allowable Catches (TACs). The survey data have shown that squid has increased in abundance and expanded their distributional range within the North Sea. In 1984 they were found in only 20% of survey stations, compared to 60% survey stations in 2014. Over this time period, SST and the Atlantic Multidecadal Oscillation are very tightly associated with the increasing squid abundance.

3.1.3 US

3.1.3.1 West coast US and Alaska

Changes in spatial distribution of fish in Alaskan waters and, the west coast of the continental U.S., has used the Vector-Autoregressive Spatio-Temporal model (VAST; Thorson 2019a). The northward center of gravity (analogous to a centroid) for Eastern Bering Sea (EBS) walleye pollock has shifted 300 km north from 1995-2018 and nearly 200 km north from 2012-2018, which is a very rapid rate of movement relative to other marine fish. The effective area occupied has increased by 250% since 2010, as the stock has expanded into the Northern Bering Sea, which is outside the standard survey area and has been sampled less frequently. Model-based estimates of survey abundance are included as alternative models in the current walleye pollock stock assessment (Ianelli et al., 2018) in order to account for this large-scale re-distribution. The distribution of fish stocks off the U.S. west coast generally has been stable or slowly moving northward, with northward shifts detected in 7 of 18 examined stocks, and semi-pelagic species are showing more frequent north/south movement (Thorson et al. 2016a). Finally, the relationship between abundance and effective area occupied (i.e., the "basin" hypothesis of MacCall 1990) in the Gulf of Alaska (GOA) and EBS were considered in a larger meta-analysis that included stocks from 6 areas including South Africa, the North Sea, and the northwest Atlantic. For example, Eastern Bering Sea arrowtooth flounder increased both their abundance and their area occupied. Across all 6 areas, a 10% increase in abundance is associated with a 0.6% increase in area occupied across the 6 areas examined, but this relationship is stronger for the Bering Sea (Thorson et al. 2016b). Across regions, fish distributions in the EBS are changing quickly whereas the U.S. west coast is changing more slowly. Across species, gadids show the strongest support for the basin model and rapid distribution shifts, whereas longer-lived rockfishes show slower distribution responses.

A series of species distribution models have been constructed for various portions of the North American coast and used to project the effects of future climate change. The largest shifts in distribution are expected along the west coast of U.S. where that spatial gradient of temperature is relatively weak (with the caveat that this area is relatively difficult to resolve in climate models due to fine-scale upwelling) (Morley et al. 2018).

3.1.3.2 East coast US

Several studies have been conducted of distribution shifts of marine fish on the east coast of the U.S., using data from bottom trawl surveys conducted annually by the U.S. National Marine Fisheries Service. For example, black bass off the northeast U.S. Atlantic coast have shifted north at a rate of 50 km per decade, with an average for demersal species in this region of 20 km per decade (Pinsky et al. 2013). In the Gulf of Mexico, a northward shift is prevented by the North American landmass, but marine fish in this area have shifted to deeper water in response to increased temperatures. Climate velocities (the speed at which temperature isotherms move) are a useful metric of climate change, and are as fast or faster in marine environments as in terrestrial systems due to weak thermal gradients in the ocean (Burrows et al. 2011). Species distribution shifts are significantly related to climate velocities, with larger changes in distribution in areas associated with faster climate velocities (Pinsky et al 2013). On average, changes in the distribution of marine fish do not lag behind the climate velocities in their region, although there is variation between species. Statistical models conducted to identify covariates (beside climate velocity) that might explain changes in fish distribution identified the von Bertalanffy K (i.e., growth rate) parameter as being statistically significant, but it had little explanatory power.

Variation between stocks in their response to changes in temperature can reflect differences in life-history traits and relevant biological mechanisms. Fish stocks off the southeast U.S. coast can respond to interannual changes in temperature, with species that prefer warmer temperatures showing increased survey abundance with increased temperature, and vice versa. The mechanism for these changes varies between stocks. For example, in star drum, cold winter temperatures results in higher overwinter mortality of juveniles in estuaries, whereas for smooth dogfish, warmer winter temperatures results in earlier migration northward and reduced abundance in the southeast U.S. survey area (Morley et al. 2017).

3.1.4 Summary of insights gained by comparing evidence of changing distribution for three regions

The three sections above summarise the main distribution changes for marine species in three focal regions: Australia, Europe, and the U.S. In all three regions, there is ample evidence that large scale distributional changes have occurred for a majority of marine species, with some consistent patterns observed across these three regions. In Australia, poleward shifts have been observed along the east coast for several marine species, such as sea urchins and octopus, with negative consequences on the balance of the ecosystem they move into (e.g., urchins grazing on kelp beds and depleted them). Although Australia does not have long-term standardised scientific surveys such as the ones established in Europe or the U.S., the use of alternative data sources such as citizen science (i.e., observations from the public) allows for detecting species shifts. Other alternative techniques such as the spatial modelling of suitable habitat areas as a strong proxy for a species distribution allows to quantify and predict future changes.

In Europe, analyses of long-term survey data have revealed changes in distribution for many commercial species. As observed in Australia, many of these changes are poleward shifts. However, in Europe where intense fishing exploitation has been going on for over a century, distribution changes are not solely climate-related. For some heavily exploited species such as Atlantic cod, distribution changes have been linked to warming but also fishing pressure to some extent. The recent survey-based assessment of distribution changes for commercial species across the Northeast Atlantic undertaken by the International Council for the Exploration of the Sea (ICES) (ICES, 2016) showed that most species have shifted their distribution, and identified both temperature (through its impact of suitable habitat area) and density-dependence (abundance impact the use of the suitable habitat available) as the main drivers of distribution, while acknowledging that other drivers may be at play.

In the US, analyses of research survey data revealed a direct link between increase in abundance and increase in area occupied, consistent with the density-dependent use of areas of suitable habitat reported in Europe. This indicates that climate-induced changes in sea temperatures may not be the only driver of change in distribution. Large-scale analyses of research survey data showed shifts in distribution for a majority of species which were mainly poleward, as seen in Australia and Europe, and /or towards deeper waters, as seen in Europe. However, not all observed changes are poleward (i.e., unidirectional). The majority are linked climate velocity (i.e., movement of isotherms), indicating the overarching and cross-species impact of warming.

In summary, changes in the spatial distribution of marine species are observed across the globe. These are overall in a poleward direction and/or sometimes towards deeper waters. Long-term standardised research surveys allow for detecting these changes. When such data are not available, alternatives do exist to record shifts (e.g., angling records, citizen science). Although shifts towards the poles and/or deeper waters are often consistent with shifts towards cooler waters as would be expected under rising sea temperatures, many other drivers can also impact these distribution shifts, including density-dependence, location of fishing grounds. Indeed, when considered individually, many species do not conform to the expected distributional response which may be due to (i) impact of other unknown driver on their distribution; (ii) a lack of data, or inability to detect distribution changes which may impact our perception of these changes; and (or) (iii) a combination of the two. When distributional shifts do occur, the consequences such as changes in trophic interactions and their impact on ecosystems may not be fully appreciated or understood.

3.2 Management implications of changing fish distributions in EU waters

The spatial distribution of a fish stock is fundamental to how quotas are derived and allocated amongst stakeholders, and which nations partake in a given fishery. The temporal persistance of a stock within the Exclusive Economic Zone (EEZ) of a given country, known as zonal attachment, is an important consideration in the proportional allocation of quota to that country (Hannesson, 2013a). Sustainable management of transboundary stocks requires inter-governmental negotiation and cooperation (Henriksen and Hoel, 2011). Many European fisheries are currently managed in accordance with regulations laid out in the EU's Common Fisheries Policy (CFP). The majority of EU stocks have transboundary spatial distributions, straddling the EEZs of multiple nations both within and outside the EU (EC, 2016). A TAC is agreed upon annually for each fish stock, and a portion of this TAC is then allocated as quota to each member state participating in the fishery (Carpenter et al., 2016). Catch quotas are apportioned to each country according to the relative stability key which gives fixed proportions by which the TAC is divided amongst the nations participating in fisheries (Dankel et al., 2015; Holden and Garrod, 1996). Relative stability is largely based on catch records from 1971-76, a time period that preceded the significant warming in the 1980s.

The current European system of fixed proportional allocations is widely recognised as insensitive to various aspects of both the biology of commercially exploited species as well as to the structure of the fishing industry (Hirst, 2015). In future, quota negotiations may need to account for natural variability in the spatial distribution of stocks (Jensen et al., 2015), whether they are changing seasonally or as part of some sort of directional trends over longer periods of time (Baudron and Fernandes, 2015). If changes are not accounted for in the allocation of quotas, disputes may arise between stakeholders. For example, between 2008 and 2013, the Northeast Atlantic mackerel stock began expanding northwards into Icelandic waters (Hannesson, 2013b). This resulted in a dispute because the government of Iceland unilaterally set themselves a quota for mackerel based on its spatial distribution shifting into their territorial waters, despite having no historical track record in the fishery (Dankel et al., 2015; Jensen et al., 2015). Other stakeholders in the fishery who had negotiated quota share through the North East Atlantic Fisheries Commission subsequently began to withdraw from associated arrangements. In this case, fixed proportional allocations under the principle of relative stability were not accepted by the new entrant to the fishery but instead based on what they perceived as a resource that was available. A system by which quota is allocated that takes into account recent changes in fish stock distributions, *sensu* zonal attachment, would be a more equitable outcome. However, it would be inherently variable which is problematic to the fishing industry which likes to be able to plan for the future with a high degree of certainty.

3.3 Methods used for analysis of distributional data for fish

A variety of methods have been used to detect whether distribution shifts are occurring, and to model past and future changes in species' distributions. Distribution shifts encompass several ecological processes including extirpation at the trailing edge, establishment and persistence at the leading edge, and differential changes in the spatial distribution of population abundance within a given range. Methods used to measure and predict how fish distributions change are often classed as either correlative, which look at statistical links between a species' range and its environment, or mechanistic, which look more into physiological traits and how these may affect future geographic ranges. Given that species distribution models provide the capacity to undertake retrospective as well as prospective assessments of fish distributions, it is important to consider how these quantitative tools can be used to measure distribution changes in, for example, species range edge or core habitats (Champion et al 2018a). It is also important to discuss approaches and data requirements for addressing these considerations in order to stimulate innovation and progress.

3.3.1 Empirical measures of species distribution

There are a number of empirical spatial statistics or indices which may be derived from research survey data which capture patterns of fish distribution (Woillez et al. 2009). Centres of gravity represent the weighted average latitude and longitude of biomass or presence, whereas the edges of the distribution can be quantified with a percentile (e.g., 1st or 5th) of the distribution of latitude/longitude. Another empirical metric is the area occupied by a given percentile of the stock, which may change independently of the location of the centroid. Statistical methods for evaluating whether distributions have changed over time include simple measures of temporal trends and interannual variability, and their relation to environmental factors. Empirical distribution functions (EDFs) can be constructed for a species distribution in a single year or set of years, and changes in the EDFs over time can be evaluated. Changing survey footprints can complicate the empirical measurement of species distribution. Trimming the data to produce a temporally consistent dataset, or using empirical metrics that account for differential sampling rates among survey strata by weighting each observation in accordance to the spatial area it represents (Perry & Smith 1994) can remedy this issue. In more extreme cases of years and/or areas having no observations, model-based measures of distributions can be used fill in gaps (Thorson et al. 2016).

3.3.2 Habitat suitability models

Habitat suitability models provide valuable information on areas of suitable environmental conditions, relative to areas of unsuitable conditions, for a given species in space and time (Elith and Leathwick, 2009). Spatial projections from these models are commonly produced on a continuous scale (e.g. from 0 to 1), requiring the identification of values that are representative of species range edges or core habitats to measure distribution changes through time. One approach to addressing this challenge involves the use of species occurrence records, independent of those used to train the initial habitat model. By plotting these against habitat projections having daily resolution, habitat suitability values that reflect conservative and ecologically realistic estimate of range boundaries and core habitats can be obtained (Champion et al., 2018a). Citizen science databases that aim to monitor species at the edges of their distribution, or identify species shifting into novel habitats are likely to prove particularly valuable for this purpose (e.g. www.redmap.org.au, Section 3.3.5).

Future projections of species' preferred environmental habitats are particularly useful for informing climate adaptation options (Hobday et al., 2016). However, the uptake of information presented in future habitat projections requires effective communication of their outputs that are tailored for end users and relevant to time-scales associated with decision-making. When projecting the future distributions of valuable target species, a useful metric is the temporal persistence (e.g. months per year) of species' suitable environmental conditions in spatially explicit regions (Champion et al., 2018b). For example, it has been proposed that the duration of environmental habitat persistence in spatially explicit domains can be considered analogous to ecological, social and economic opportunities (Champion et al., 2018b).

Ecologically, the temporal persistence of suitable habitat within novel environments is a critical factor influencing range-shifting species. Bates *et al.* (2014) proposed that climate-driven range extensions occur as a sequence of arrival, population increase and persistence, and that confidence in species range change also increases as 'establishment' progresses across this spectrum. Therefore, increased temporal persistence of suitable environmental habitat at species range edges indicates a greater opportunity for individuals to progress through critical life-history stages, allowing for population increases and, ultimately, the establishment of species in novel environments (Ling *et al.*, 2009b).

Socially and economically, changes in the temporal persistence of suitable habitats for valuable or iconic species may equate to shifts in commercial and recreational fishing opportunities (Champion et al. 2018b). Similarly, the economic profitability of tourism ventures, such as charter fishing operations or SCUBA diving tours, may be affected by these changes. When communicated as a measure of opportunity, future predictions of temporal habitat persistence can provide a quantitative basis for the development of climate change adaptation strategies. For example, predictions of increased habitat persistence for commercially valuable species may support greater investment from fishers, such as the purchase of gear or licences, whereas predicted declines in habitat persistence may indicate a potential need to divest or diversify (Champion et al. 2018b).

Similar modelling approaches have been used in a number of European studies in recent years. For example, future distributional changes of a number of commercially exploited species were modelled using an ensemble of three distribution models, which predicted that some warm-affinity species such as squid, sea bass and pilchard would see an increase in their suitable habitat by the middle of the century, and would have a latitudinal shift around the UK of hundreds of kilometres (Defra, 2013). The study, which used global climate change projections, predicted that colder-affinity species such as halibut and cod would see a shrinking of their suitable habitat leading to a northward shift in distribution. Lenoir et al. (2011) also modelled (using Ecological Niche Models) 8 commercially exploited species in the Northeast Atlantic, predicting a trend of poleward movements of species, with distributions generally tracking favourable climatic conditions to varying degrees.

3.3.3 Generalized additive models

Generalized additive models (GAMs) are widely used to infer the relationships between environmental distributions and stock distributions. GAMs developed in the Eastern US have focussed on delta-models, which combine the modeling of occurrence with the modeling of biomass conditional on occurrence. Each of these two modeling stages incorporate covariates such as bottom and surface temperatures, seafloor rugosity, and sediment grain size. These types of models have been applied to marine stocks in both Atlantic and Pacific U.S. waters, based on several region-specific trawl surveys (Morley et al. 2018). Cases where the models give unrealistic predictions of distributions can occur because the simple correlative approach may not account for ontogenetic changes in habitat use. For example, gray snapper off the U.S. east coast overwinters in estuaries as juveniles, but the temperatures experienced in these estuaries would not be typically encountered when juveniles mature and move to their adult habitats. These complexities can be addressed by mechanistic models tailored for each species. Some assumptions of either correlative or mechanistic statistical models fit to empirical data are: 1) the realized niche rather than the fundamental niche is being modelled (with the realized niche being influenced by species interactions, fishing, etc.); and 2) the spatial distributions are in equilibrium with the environment, with the relationships between distributions and the environment not changing over time.

High resolution, downscaled climate projections for the north-west European shelf have also been used in modelling similar species. For example, a GAM trained on North Sea fish indicated that some of the species had moved as far deep as they were able, and in fact they will be constrained more by depth in the future than temperature (Rutterford et al., 2015). These downscaled projections have also been nested within global climate model outputs to look at species which are more widespread than only Europe, showing that many non-native species and harmful algal species may be able to spread further around north-west Europe than currently (Townhill et al., 2017; 2018). Future developments of these models will be made as more climate scenarios are modelled, and more parameters are added, such as oxygen and pH. The addition of benthic substrates will further show constraints to species shifts, and including trophic levels and traits rather than only single species shifts, will help us understand foodweb interactions and other limitations to species shifts.

3.3.4 Climate attribution and skill testing

In Alaska, spatio-temporal models have been used to estimate population density for multiple species, times, and locations, and these model-derived estimates can be used as a “common currency” capturing the stock, ecosystem, habitat, and climate assessments. Spatio-temporal models have been used as a spatial “model of intermediate complexity”, estimating biological reference points, stock status, and species interactions when fitting to spatial survey data for four species in the GOA. Climate attribution analysis (i.e., the impact of multiple causal drivers for distribution shifts are analyzed) has been applied to Alaska pollock, where size-structure and temperature are not sufficient in isolation to explain the 200 km northward shift in this stock (Thorson et al. 2017). Retrospective skill testing was evaluated for twenty species in the EBS to determine model performance relative to a null (persistence) forecast. This skill test showed that a habitat envelope model has worse performance than a persistence forecast, while a regression of center-of-gravity on environmental conditions explains 2-6% of variance and a spatio-temporal model explains 8-25% of variance (Thorson 2019b). Use of skill-testing as a development tool and test bed for identifying methods that are useful to forecast distribution shifts in a given management context is recommended.

3.3.5 Citizen science initiatives

Australia has a large coastal population with many Australians actively engaged in fishing and/or diving. To take advantage of this, a national citizen science project called Redmap, or the Range Extension Database and Mapping project (http://www.redmap.org.au/) was developed. This project allows Australians to share sightings of marine species that are uncommon in their local seas. Over time, Redmap uses this source of "citizen science" data from fishers and divers to map which Australian marine species may be extending their distribution range in response to changes in the marine environment, including ocean warming. To ensure quality, each observation submitted is independently verified by the scientific expert for the given species (Pecl et al in review).

3.3.6 Other methods

Dynamic Energy Budget (DEB) models are another way to include physiological processes when accounting for changing "seascapes" of environmental conditions (Kooijman, 2010). DEBs have been used to predict size- and season-specific fish distributions based on temperature and food conditions. For example, DEBs were used to identify coastal zones that have become unsuitable for juvenile North Sea plaice in recent decades (Teal et al., 2012). Aerobic scope models consider future habitat suitability by examining the relationship between aerobic scope and the environment (Teal et al., 2018). Cucco et al. (2012) used aerobic scope measurements and oxygen projections to predict the suitable habitat for flathead grey mullet in the Mediterranean, and Marras et al. (2015) looked at future thermal habitat in a native species, *Sarpa sarpa*, and an invasive rabbitfish in the Mediterranean. Individual-based models (IBMs) focus on individuals or groups and their interactions with the environment (DeAngelis and Grimm, 2014). For example, an IBM has been parameterised for the western component of the north east Atlantic mackerel stock (Boyd et al., 2018). Larval cod growth and survival has been modelled to the end of the century, suggesting a decline in survival and increased larval metabolic costs (Kristiansen et al., 2014). Seabass has also been modelled using an IBM to investigate the factors affecting sea bass settlement on nursery grounds of the northern sea bass stock (Beraud et al., 2018). The model predicted that larval duration was driven by water temperature, showing an increase in duration from the south west to north east areas of the northern sea bass stock.

4 Climate change impacts on individual fish growth

A strong body of knowledge underpins our physiological understanding of the Temperature size rule (TSR), which proposes that juvenile growth rates are higher in warmer waters due to higher metabolic rates with rapid early growth leading to a lower maximum (adult) size-at-age (Daufresne et al 2009; Forster and Hirst 2012). Evidence of the TSR is strongest for aquatic ectotherms (Forster et al. 2011). Several inter-linked propositions related to the TSR can be made for ectotherms in warming ecosystems. First, for a given population the decrease in maximum body size will coincide with the period of warming. Second, the universality of the TSR implies that a synchronous decrease in maximum body size should be detectable in multiple populations occupying the same ecosystem (Section 4.1.2). Growth rates are also impacted by other factors, including food availability and density. Unlike temperature, these factors tend to vary asynchronously across co-occurring populations. Testing for a coherent (i.e., consistent with established physiology and ubiquitously observed) biological response on a global scale requires standardised data collected on time scales that are long enough to be impacted by climate change (Section 4.4) and consistent analytical methodology (Section 4.5).

4.1 Review of climate impacts on individual growth rates

4.1.1 Australia

The waters of south east Australia have rapidly warmed over the last 70 years (Ridgway 2007, Shears and Bowen 2017), and recently experienced a marine heatwave of unprecedented magnitude, intensity and duration (Oliver et al. 2017). These changing conditions have had a significant impact on the region's fish and fisheries, most ubiquitously seen in the number and extent of species' distribution shifts (Section 3.1.1). Warming waters have also directly (via physiological pathways) or indirectly (via alterations in food webs or species interactions) impacted on the growth of south east Australian marine fishes (e.g. Thresher et al. 2007, Neuheimer et al. 2011, Morrongiello and Thresher 2015). It is, however, important to acknowledge that the region sustains major commercial fisheries (Tilzey and Rowling 2001), and elevated mortality rates associated with harvest can select for faster life histories (Roff 1992, Law 2000). Disentangling the relative importance of warming and harvest can be difficult as both stressors select for elevated juvenile growth and overall smaller body size, and can act in synergy (Waples and Audzijonyte 2016, Morrongiello et al. accepted). Regardless of the driver, a shift to smaller fish has implications for the strength and direction of species interactions (Audzijonyte et al. 2013), and the region's fisheries productivity and management (Audzijonyte et al. 2016).

The majority of growth rate studies in south east Australia have focussed on using the growth information naturally archived in otoliths. The re-analysis of historical collections has allowed for the recreation of growth time series over a century in length (Thresher et al. 2014). These data have proved invaluable to understanding the causes and consequences of growth rate change beyond the scope of modern fisheries surveys (Morrongiello et al. 2012). Here, we present three case studies illustrating how otolith-based growth data can be used to explore climate and fishing-induced changes in fish growth on scales ranging from individuals to assemblages.

Purple wrasse is a temperate fish species inhabiting near shore reefs in south east Australia that displayed rapidly increasing growth rate during the 1990s (Morrongiello et al. accepted). A commercial fishery for the species began in 1990 targeting large adults for the live fish trade. This fishing activity induced a predictable increase in the average growth as older fish were released from density dependence (Figure 4a). Concurrently, warming waters also caused an acceleration in population-averaged growth (Figure 4b). At the individual scale, a synergy between fishing and warming resulted in a 50% reduction in growth thermal reaction norm diversity (Figure 5), caused primarily by the harvest of larger individuals that showed positive temperature responses. It is speculated that fishing inadvertently selected on individual thermal sensitivity or disrupted social hierarchies and associated resource availability, resulting in a loss of growth phenotypes which in turn could reduce the species' capacity to respond to future warming.

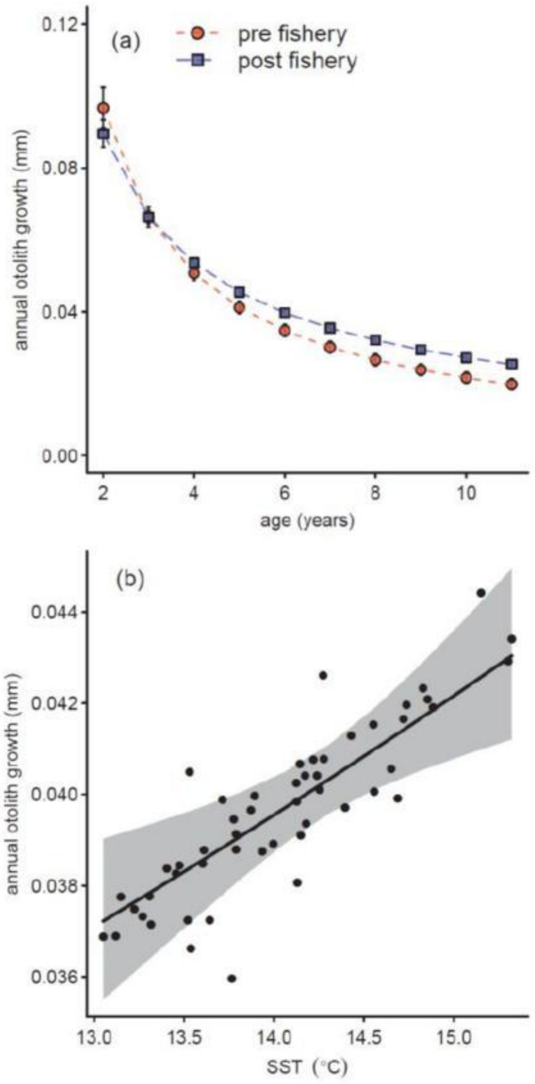


Figure 4: Tasmanian purple wrasse annual otolith growth (annuli width mm ± 95% CI) as a function of extrinsic factors. (a) Age-dependent annual otolith growth by fishery status (circles: pre-fishery 1980-1989; squares: post-fishery 1990-1999); and (b) annual otolith growth as a function of SST (Morrongiello et al. accepted).

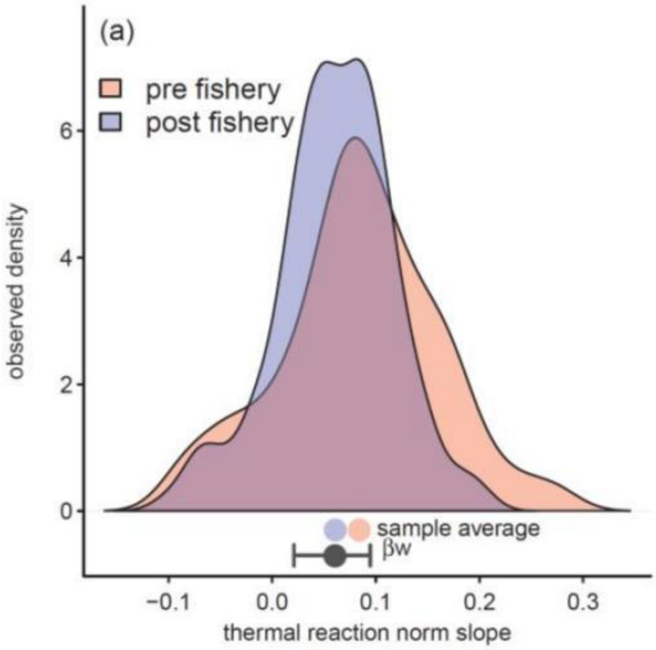


Figure 5: Density plot of observed purple wrasse thermal reaction norms in the pre- and post-fishery periods. Positive reaction norms occur when a fish's growth responds more positively to warming compared to the population average. Thermal reaction norms were derived from mixed models that portioned otolith growth variation into within-individual phenotypic plasticity and among individual effects that reflect persistent environmental or genetic differences (from Morrongiello et al. accepted).

A multi-stock analysis of tiger flathead growth (Morrongiello and Thresher 2015) detected considerable variability in stock-averaged growth rate trends, with increases ranging from 0.7 to 2.5% per year over the 40 year study period (Figure 6). Increased growth was strongly related to regional warming, with growth increasing from between 7.29 to 41.21% per °C (Figure 7). There was no apparent fishing signal in these growth trends, although it must be acknowledged that the fishery dependent catch per unit effort (CPUE) index used could have limited sensitivity to actual population density. These tiger flathead results are consistent with warming induced rapid increases in juvenile growth for other coastal and shelf species in the region (Thresher et al. 2007, Neuheimer et al. 2011).

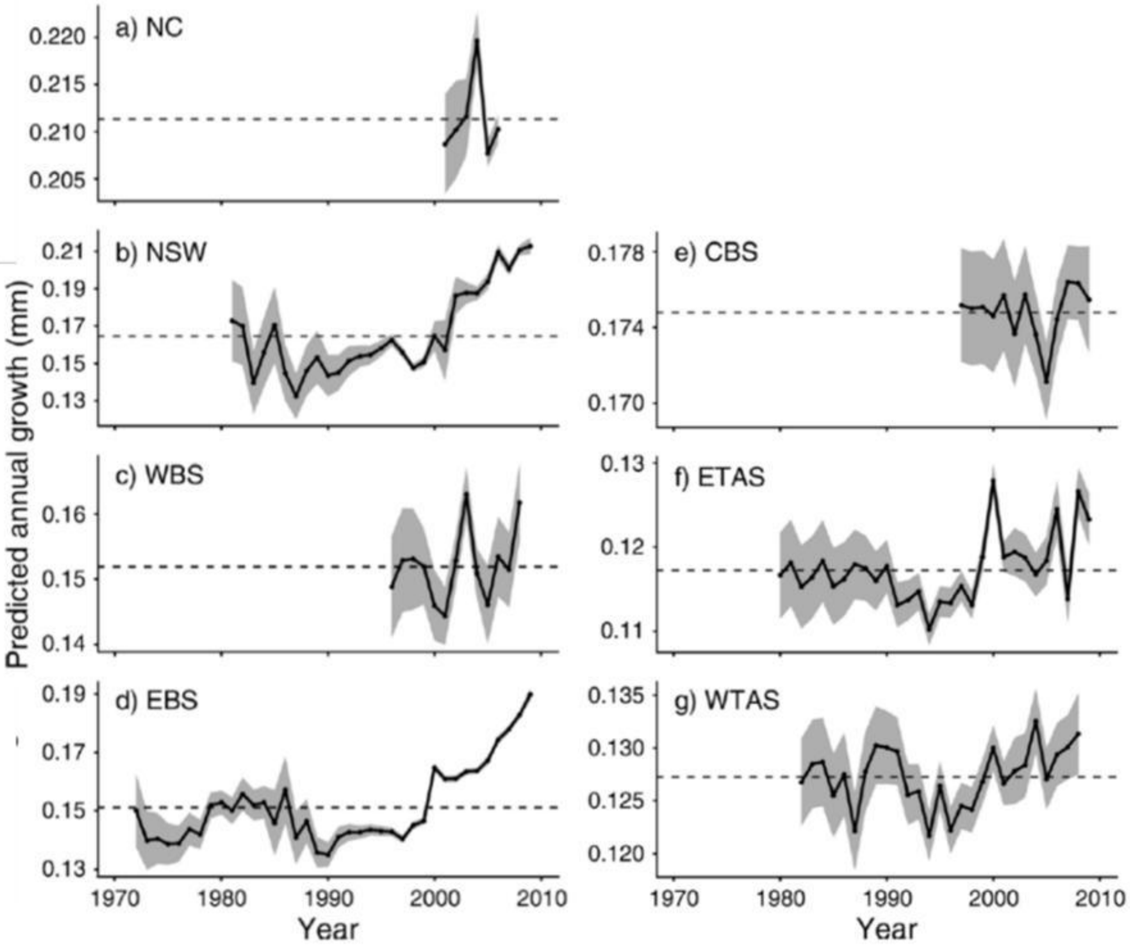


Figure 6: Predicted annual average otolith growth variation for tiger flathead across seven fishing areas. (a–g) Annual growth variation represented by Year random-effect conditional modes (best linear unbiased predictors [BLUPs] ± SE). The dashed lines in each panel represent long-term average growth (Morrongiello and Thresher 2015).

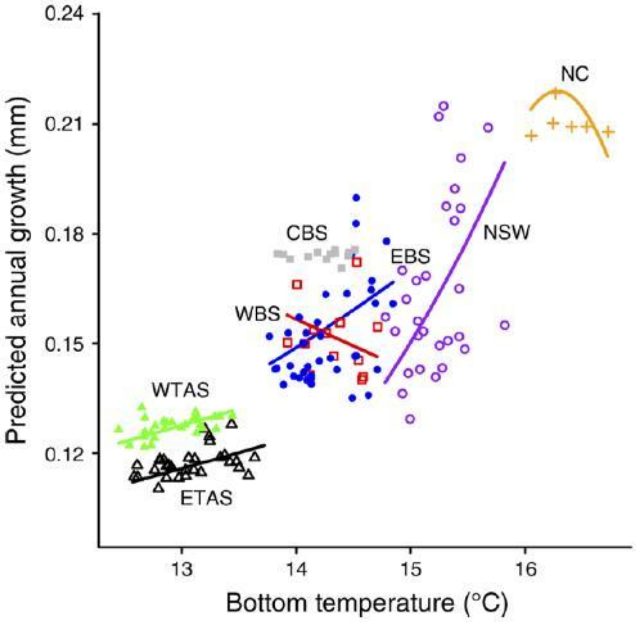


Figure 7: Predicted annual growth of two-year-old male tiger flathead (Age at capture held at mean value) by bottom temperature for each area. Points are Year random-effect conditional modes (BLUPs) generated from optimal intrinsic-effect models and represent average extrinsic growth variation. Fishing area codes match those in Figure 6 (Morrongiello and Thresher 2015).

Ongoing research aims to explore commonalities and differences in the drivers of fish growth variation across south east Australia. 56 otolith-based growth time series have been developed from 21 species across the region using mixed effects models (Morrongiello and Thresher 2015). Individual time series range from 11 to 96 years in length and represent juvenile and adult growth from fish inhabiting tide pools, coastal, shelf and slope habitats, and the deep. Dynamic Factor Analysis (DFA, see section 4.4.2) was used to explore the possibility of common modes of growth variation across the region. The best DFA model detected four common trends, indicating substantial growth synchrony within and across species across the region (Figure 8). Such synchrony could be indicative of factors other than the TSR. Data suggests dramatic shifts in growth rate beginning in the 1950s, and more recently in the 1990s. Preliminary analyses suggest that these common growth trends are related to both climate and fishing effects.

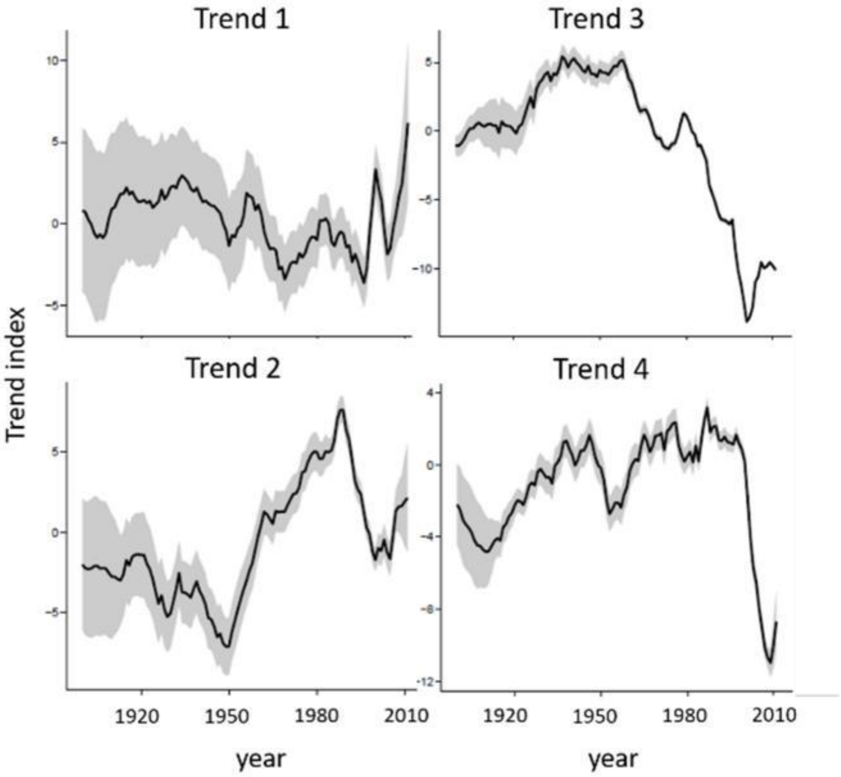


Figure 8: The four common trends in south east Australian fish growth (± SE), as determined by DFA.

4.1.2 UK

Over the past 30 years, water temperatures in the North Sea have increased by 0.2–0.6 °C per decade. During this period, declining body sizes have been observed in haddock (*Melanogrammus aeglefinus*) (Baudron et al., 2011), herring (*Clupea harengus*) (Brunel & Dickey-Collas, 2010), and plaice (*Pleuronectes platessa*) (van Walraven et al., 2010), three species differing in their life histories, trophodynamics and vertical distribution in the water column. This response is consistent with the TSR. However, a complication in establishing direct causality between warming temperatures and decreasing body sizes in commercial species is disentangling the effect of temperature from other factors possibly affecting body size including: (i) density-dependent competition for resources; (ii) fisheries-induced evolution; (iii) size-selective fishing mortality leading to a size artefact. Disentangling the relative effects on growth of these three factors and temperature on a species-specific basis can prove challenging when two or more factors are confounded. However, unlike temperature the impact of any of these three factors is likely to be highly species-specific.

In a study by Baudron et al. (2014) length-at-age data for eight commercial species of the North Sea were obtained from research vessel surveys. Data were split between northern and southern sub-stocks to account for the north-south temperature gradient, and by sex for dimorphic flatfish species. This resulted in 13 sub-stocks spanning a wide range in different life-history traits. For each sub-stock, a von Bertalanffy growth model was fitted on a cohort-by-cohort basis. A DFA (Zuur, 2003) model was used to detect common trends across the sub-stocks' time series of asymptotic lengths (L_∞). The majority of sub-stocks exhibited a decline in L_∞ (Figure 9). The best DFA model identified two common trends, with the dominant trend positively and equally related to nine of the 13 sub-stocks, corresponding to six of the eight species considered. This trend showed a decline in L_∞ synchronous with increasing sea temperatures (Figure 9), and this common trend and the sea temperature were inversely significantly correlated (Table 2). These results are consistent with the TSR that has been postulated in simulation studies (e.g., Cheung et al. 2014). The DFA was repeated on the three species-specific factor potentially impacting size (density-dependence, approximated by abundance; fishing-induced evolution; approximated by fishing mortality; size artefact, approximated by mean cohort age) for the eight sub-stocks supporting the common declining trend in L∞. No common trend was identified for any of these three species-specific factors, indicating that the increasing temperature is the most likely driver behind the common trend in declining body size observed here across species.

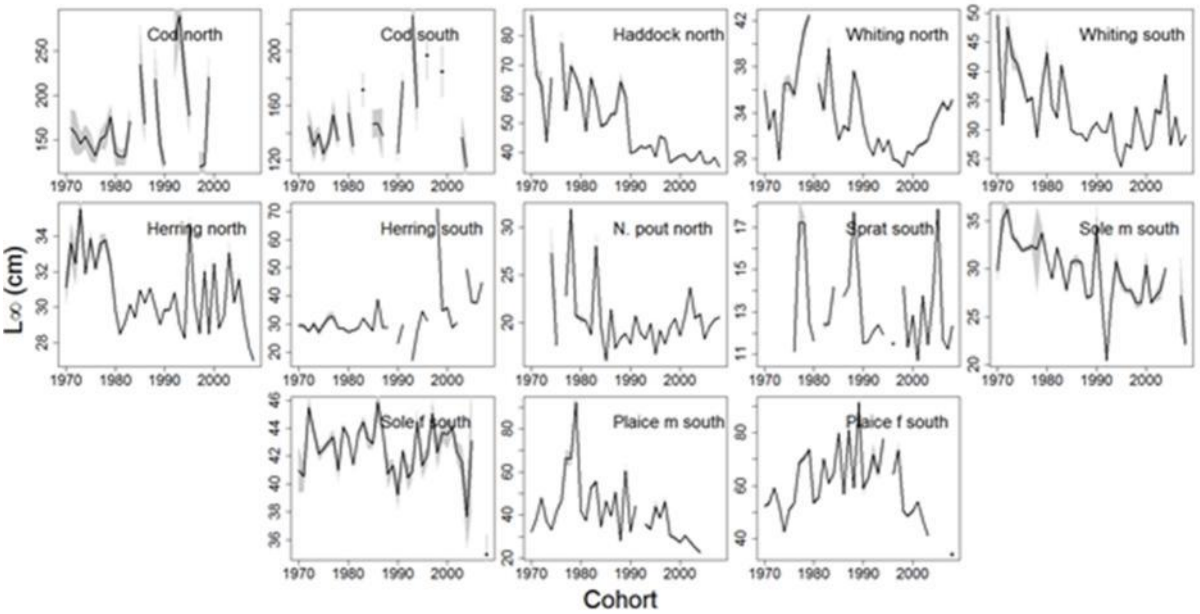


Figure 9. Trends in asymptotic length (L∞) for the 13 sub-stocks considered (Baudron et al. 2014).

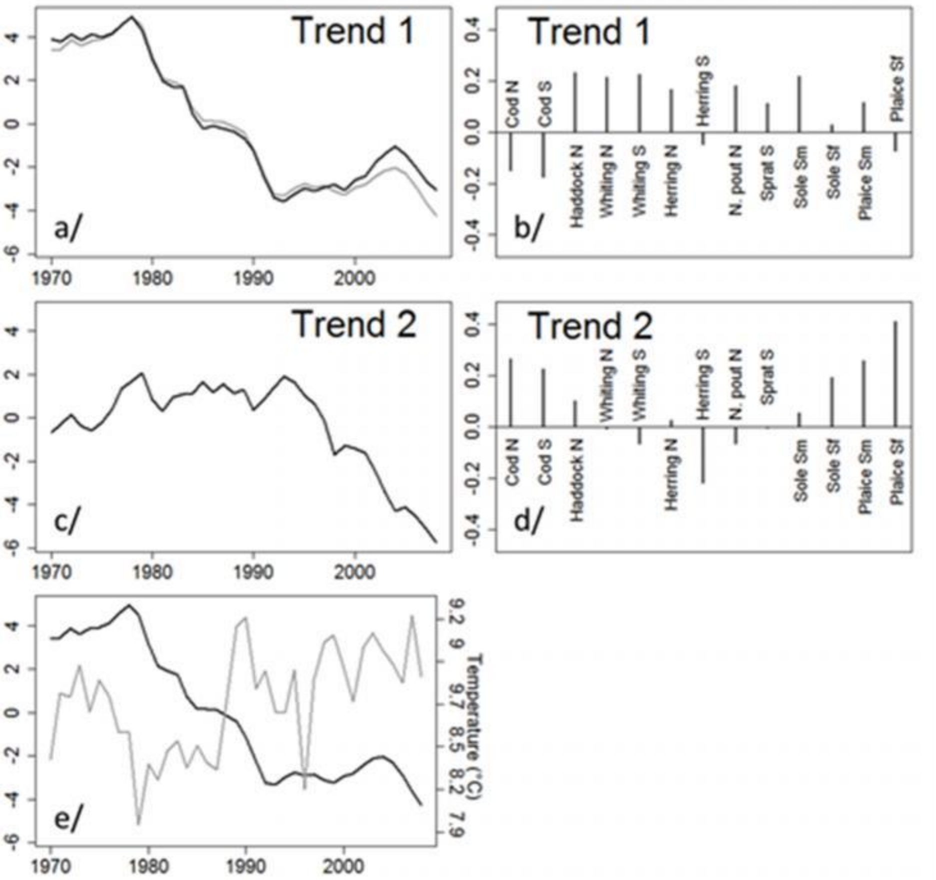
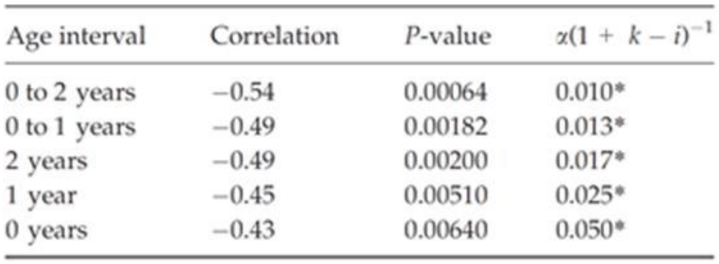
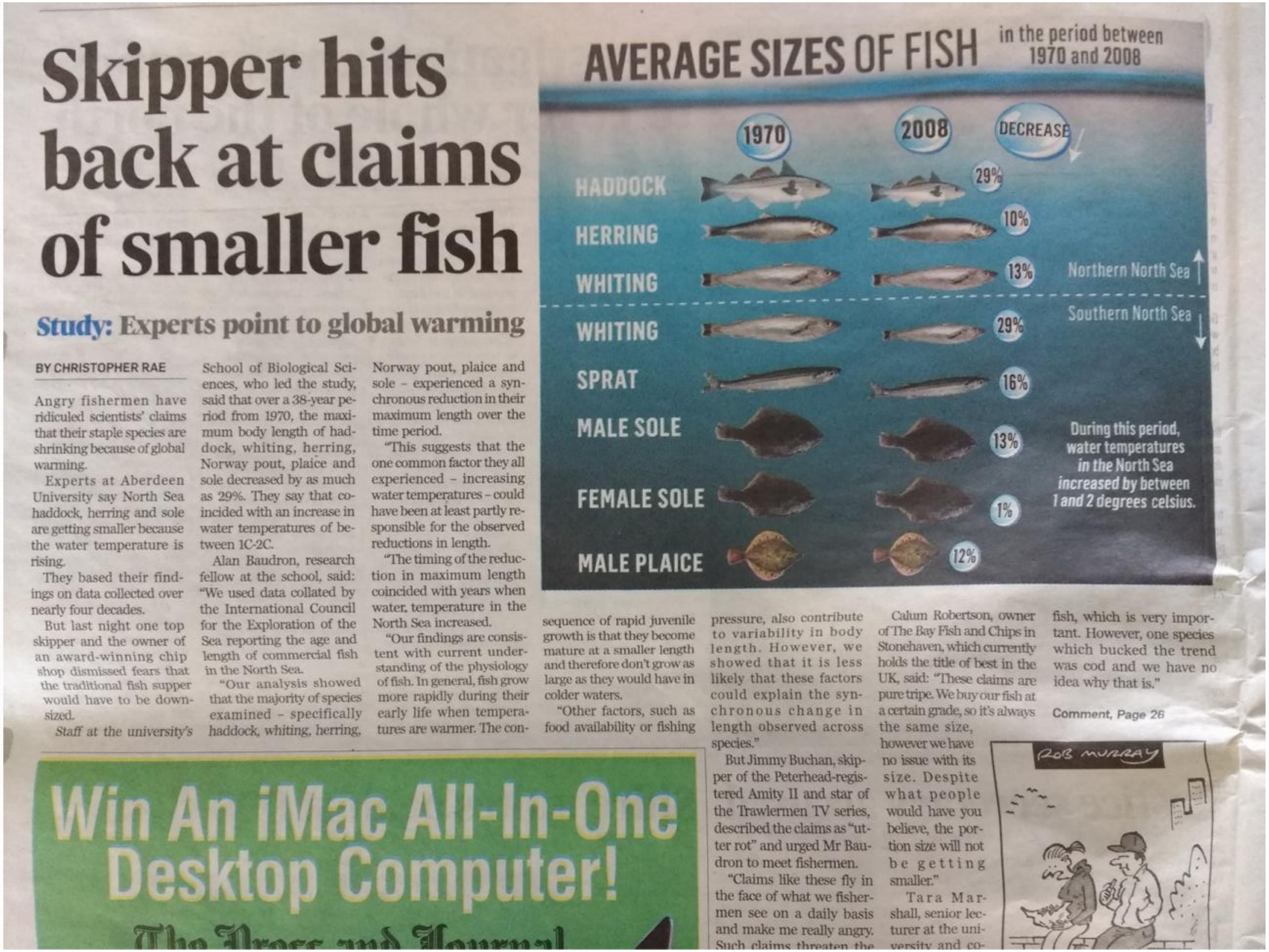


Figure 10. Results from the DFA: common trends given by the best candidate model (panels a and c) to describe L_∞ time variations over time and the corresponding factor loadings for the thirteen sub-stocks (panels b and d). In panel a, the grey line corresponds to the common trend given by a model fitted with one common trend, indicating that the trend in panel a (Trend 1) is the dominant trend. In panel e the Trend 1 is plotted along with the average sea temperature (grey line). From Baudron et al. (2014).



Age interval	Correlation	*P*-value	$\alpha(1 + k - i)^{-1}$
0 to 2 years	−0.54	0.00064	0.010*
0 to 1 years	−0.49	0.00182	0.013*
2 years	−0.49	0.00200	0.017*
1 year	−0.45	0.00510	0.025*
0 years	−0.43	0.00640	0.050*

Table 2. Estimated correlations between sea temperature and Trend 1 and their corresponding P-values, at different lags. Significance was adjusted by a sequential Bonferroni correction: the ordered P-values were compared with the inequality, Pi ≤ $\alpha(1 + k\text{-}i)^{-1}$, where α is the confidence level to test for significance (0.05), K is the number of correlation tests carried out and i is the rank of the correlation considered. Correlations for which the inequality is met are significant (*). From Baudron et al. (2014).



Skipper hits back at claims of smaller fish

Study: Experts point to global warming

BY CHRISTOPHER RAE

Angry fishermen have ridiculed scientists' claims that their staple species are shrinking because of global warming.

Experts at Aberdeen University say North Sea haddock, herring and sole are getting smaller because the water temperature is rising.

They based their findings on data collected over nearly four decades.

But last night one top skipper and the owner of an award-winning chip shop dismissed fears that the traditional fish supper would have to be downsized.

Staff at the university's School of Biological Sciences, who led the study, said that over a 38-year period from 1970, the maximum body length of haddock, whiting, herring, Norway pout, plaice and sole decreased by as much as 29%. They say that coincided with an increase in water temperatures of between 1C-2C.

Alan Baudron, research fellow at the school, said: "We used data collated by the International Council for the Exploration of the Sea reporting the age and length of commercial fish in the North Sea.

"Our analysis showed that the majority of species examined - specifically haddock, whiting, herring, Norway pout, plaice and sole - experienced a synchronous reduction in their maximum length over the time period.

"This suggests that the one common factor they all experienced - increasing water temperatures - could have been at least partly responsible for the observed reductions in length.

"The timing of the reduction in maximum length coincided with years when water, temperature in the North Sea increased.

"Our findings are consistent with current understanding of the physiology of fish. In general, fish grow more rapidly during their early life when temperatures are warmer. The consequence of rapid juvenile growth is that they become mature at a smaller length and therefore don't grow as large as they would have in colder waters.

"Other factors, such as food availability or fishing pressure, also contribute to variability in body length. However, we showed that it is less likely that these factors could explain the synchronous change in length observed across species."

But Jimmy Buchan, skipper of the Peterhead-registered Amity II and star of the Trawlermen TV series, described the claims as "utter rot" and urged Mr Baudron to meet fishermen.

"Claims like these fly in the face of what we fishermen see on a daily basis and make me really angry. Such claims threaten the

Calum Robertson, owner of The Bay Fish and Chips in Stonehaven, which currently holds the title of best in the UK, said: "These claims are pure tripe. We buy our fish at a certain grade, so it's always the same size, however we have no issue with its size. Despite what people would have you believe, the portion size will not be getting smaller."

Tara Marshall, senior lecturer at the university and co-

fish, which is very important. However, one species which bucked the trend was cod and we have no idea why that is."

Comment, Page 26

AVERAGE SIZES OF FISH in the period between 1970 and 2008

	1970	2008	DECREASE
HADDOCK			29%
HERRING			10%
WHITING			13%
WHITING			29%
SPRAT			16%
MALE SOLE			13%
FEMALE SOLE			1%
MALE PLAICE			12%

During this period, water temperatures in the North Sea increased by between 1 and 2 degrees celsius.

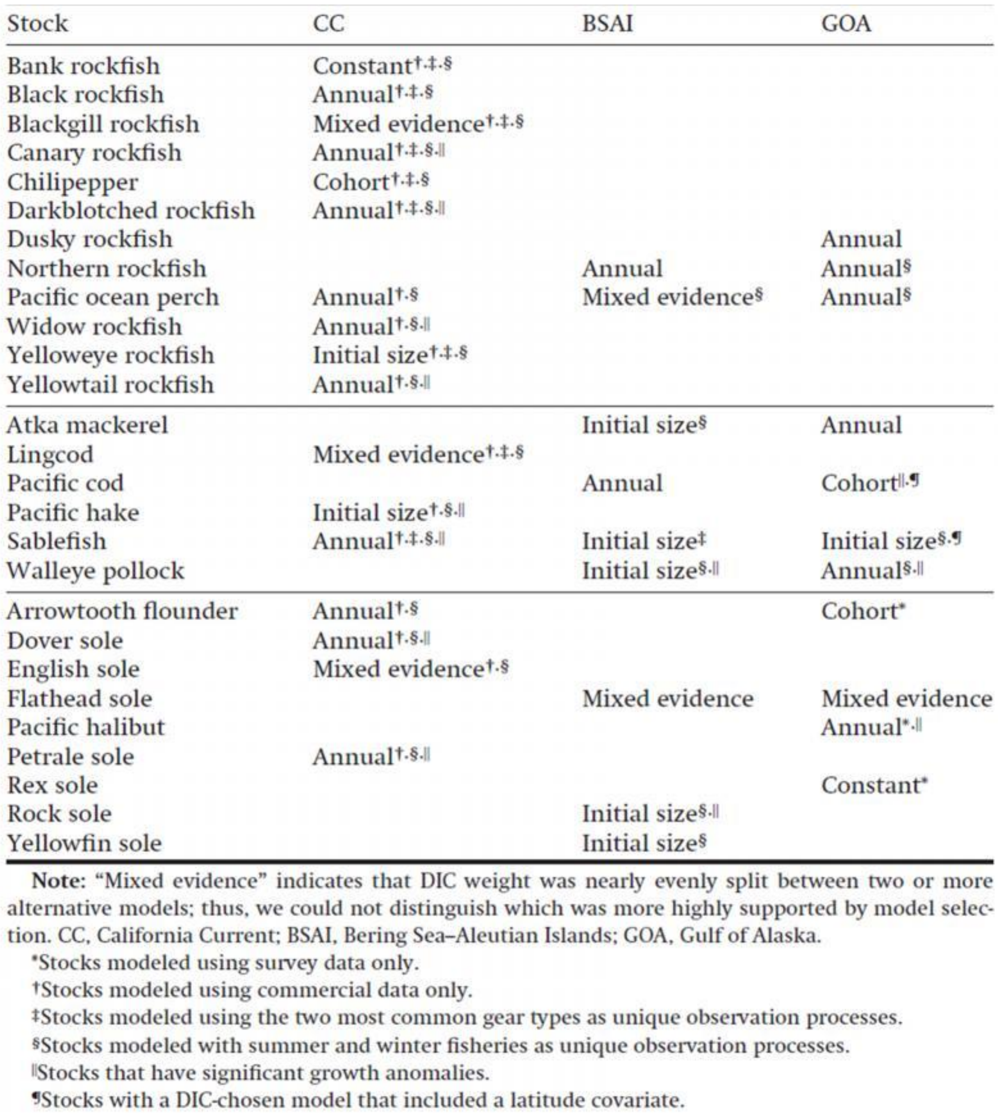
Figure 11. Newspaper article *from the Press and Journal published 29/1/2014.*

When it was originally published, Baudron et al. (2014) generated world-wide press interest focussing on the “shrinking fish” narrative. The Scottish fishing industry was very sceptical about the research (Figure 11). Although the negative response by the industry was understandable it served to illustrate a lack of understanding of the underpinning growth responses to warming temperatures (TSR) that was the scientific basis of the analysis. Scientists have access to age and length data while the industry only observes length. Having age gives scientists the ability to fit growth models on a cohort-by-cohort basis. This is an opportunity to improve communication between climate scientists and the industry.

4.1.3 US

4.1.3.1 West coast US and Alaska

In the Northeast Pacific, there is substantial temporal variation in growth rates across groundfish species. A total of 37 groundfish populations (stocks) were analysed across three large marine ecosystems, California Current (CC), Bering Sea/Aleutian Islands (BSAI), and GOA using the state-space framework described below (Section 7.4.2). Model selection supported a model including growth variation for 29 of these stocks (78.38%); however, only 13 stocks showed substantial growth variation across years, as measured by at least four years of the time series having a credible interval that did not overlap zero. The type of growth variation that was supported by model selection varied between ecosystems (Table 3). In the BSAI, most populations experienced variation primarily in size at recruitment to the fishery, whereas, in the GOA and CC ecosystems, most populations experienced temporal variation patterns that were shared across ages (Table 3).



Stock	CC	BSAI	GOA
Bank rockfish	Constant[†,‡,§]		
Black rockfish	Annual[†,‡,§]		
Blackgill rockfish	Mixed evidence[†,‡,§]		
Canary rockfish	Annual[†,‡,§,‖]		
Chilipepper	Cohort[†,‡,§]		
Darkblotched rockfish	Annual[†,‡,§,‖]		
Dusky rockfish			Annual
Northern rockfish		Annual	Annual[§]
Pacific ocean perch	Annual[†,§]	Mixed evidence[§]	Annual[§]
Widow rockfish	Annual[†,§,‖]		
Yelloweye rockfish	Initial size[†,‡,§]		
Yellowtail rockfish	Annual[†,§,‖]		
Atka mackerel		Initial size[§]	Annual
Lingcod	Mixed evidence[†,‡,§]		
Pacific cod		Annual	Cohort[‖,¶]
Pacific hake	Initial size[†,§,‖]		
Sablefish	Annual[†,‡,§,‖]	Initial size[‡]	Initial size[§,¶]
Walleye pollock		Initial size[§,‖]	Annual[§,‖]
Arrowtooth flounder	Annual[†,§]		Cohort[*]
Dover sole	Annual[†,§,‖]		
English sole	Mixed evidence[†,§]		
Flathead sole		Mixed evidence	Mixed evidence
Pacific halibut			Annual[*,‖]
Petrale sole	Annual[†,§,‖]		
Rex sole			Constant[*]
Rock sole		Initial size[§,‖]	
Yellowfin sole		Initial size[§]	

Note: "Mixed evidence" indicates that DIC weight was nearly evenly split between two or more alternative models; thus, we could not distinguish which was more highly supported by model selection. CC, California Current; BSAI, Bering Sea–Aleutian Islands; GOA, Gulf of Alaska.

[*] Stocks modeled using survey data only.

[†] Stocks modeled using commercial data only.

[‡] Stocks modeled using the two most common gear types as unique observation processes.

[§] Stocks modeled with summer and winter fisheries as unique observation processes.

[‖] Stocks that have significant growth anomalies.

[¶] Stocks with a DIC-chosen model that included a latitude covariate.

Table 3. Model selection results (Stawitz et al. 2015), aggregated by ecosystem and stock, with stocks grouped into families or similar morphologies.

Unlike the Australian (Section 4.1.1) and North Sea (Section 4.1.2) examples, time series trends of growth variation did not exhibit synchrony across species, and only a minority of stocks exhibited temporal trends. GOA Pacific halibut (*Hippoglossus stenolepis*) and CC Dover sole (*Microstomus pacificus*) were the only species to exhibit decreasing size-at-age over time. CC Pacific hake (*Merluccius productus*) and sablefish (*Anoplopoma fimbria*) both exhibited temporal trends in size-at-age, but their average size-at-age increased over the examined time series. An important caveat is that three of these four populations were analyzed using only fishery-dependent data, therefore these temporal trends may be capturing changes in sampling and not changes in size-at-age. A larger number of species (9) exhibited variation that had substantial interannual variation, but this variation was centered around zero for the time series (Figure 12) suggesting no directional trend over the full time period.

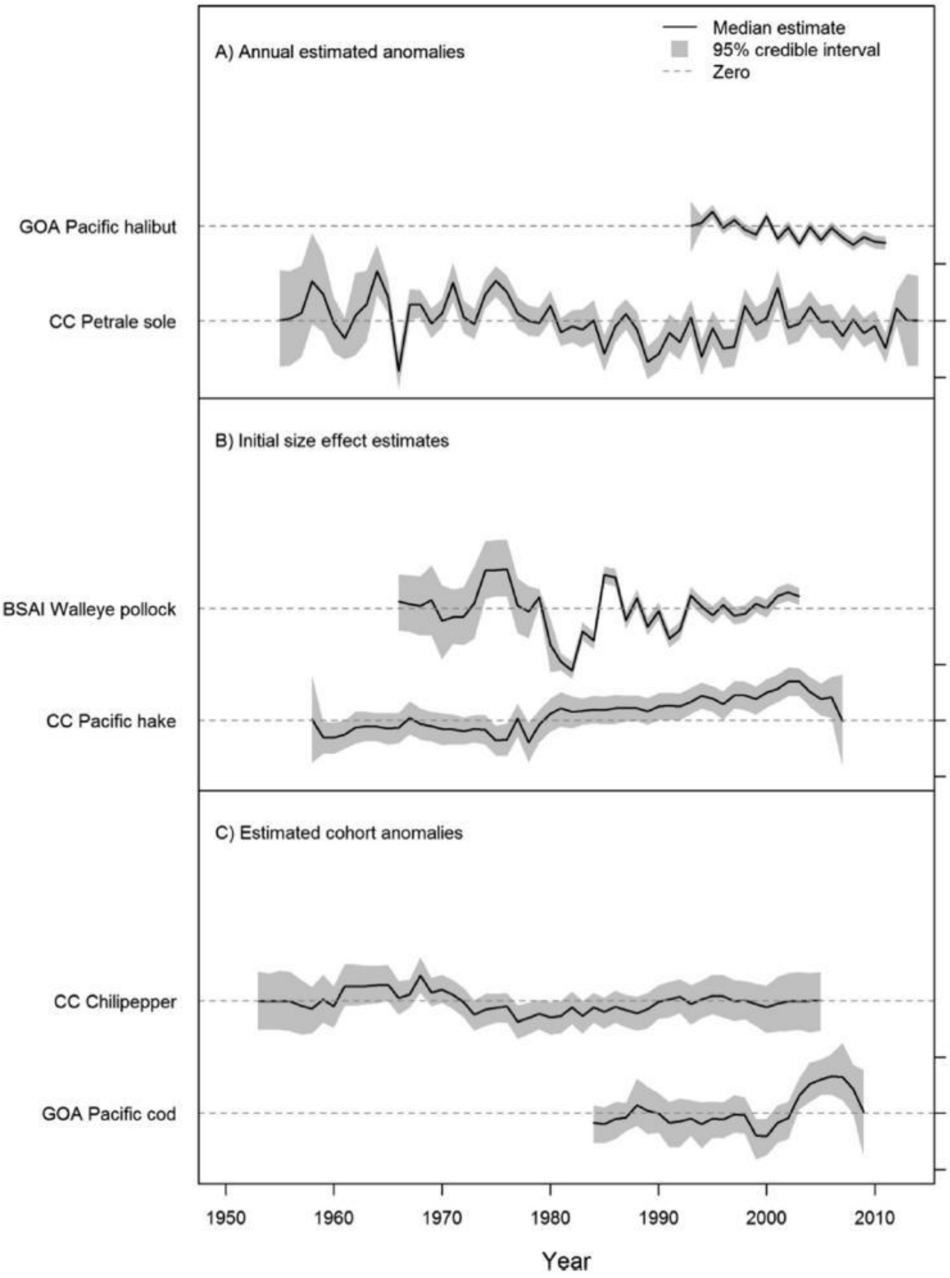


Figure 12. Growth anomaly estimates for six stocks (from Stawitz et al. 2015). The x-axis represents anomaly year for panel A and birth year for panels B and C. (A) The annual growth anomaly model was chosen for GOA Pacific halibut and CC petrale sole. These are examples of stocks that experienced highly variable growth anomalies. Credible intervals rarely overlap zero for both stocks, but petrale sole's dominant variation appears to be periodic and not following a particular trend, while halibut experience monotonically decreasing growth anomalies. (B) The initial size effect model was chosen for BSAI walleye pollock and CC Pacific hake. Initial size effects had lower interannual variability but clear periods of sustained positive or negative initial size effects. (C) The cohort growth anomaly model was chosen for CC chillipepper rockfish and GOA Pacific cod. Cohort anomalies were, on average, smaller in magnitude and smoother over the length of the time series.

4.1.4 Summary of insights gained by comparing evidence of changing growth rates for three regions

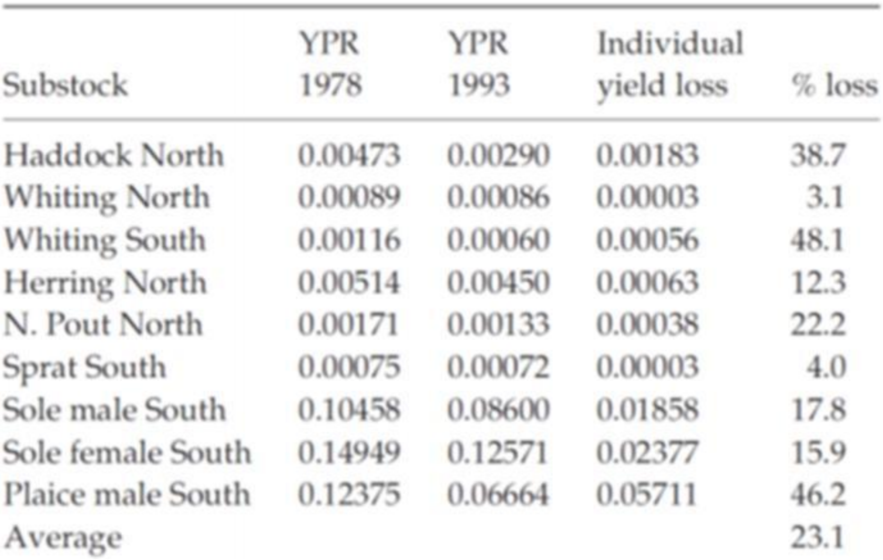
Unlike climate impacts on spatial distribution, research into broad-scale, cross-species impacts of climate on individual growth rates is at a much earlier stage of development. The TSR provides a strong theoretical underpinning for expecting a shift towards smaller body sizes in warming ecosystems. There is some support for the TSR in Australian waters (e.g. Thresher et al. 2007, Section 4.1.1) and reasonably strong empirical support in the North Sea (Baudron et al. 2014, Section 4.1.2). The lack of a consistently strong cohort effect on growth rates in US stocks on the west coast could be a result of the more complex oceanography associated with the Pacific coast, e.g., upwelling, which might mean that there is no overall trend towards warming. A lack of a growth response in an area that is not, in fact, warming is consistent with the TSR.

The implications of the TSR for fisheries yields are considerable: increased temperatures result in faster juvenile growth and smaller adult body sizes which result in decreased yields (Section 4.2.1). The TSR therefore needs more comprehensive testing through a coordinated programme research. There is a wealth of age/length data in government laboratories around the world and the workshop reviewed databases available for European, Icelandic and Norwegian waters (Section 4.3.1), the US (Section 4.3.2), and Chile. While the von Bertalanffy growth model is often the starting point for modelling (Section 4.1.2) the increase in size over time there are other possible approaches (reviewed in Section 4.4). A subset of the workshop participants agreed to undertake a coordinated comparison of different modelling approaches on a range of available datasets following the workshop. The results will be presented at the upcoming ICES Annual Science Meeting in September 2019 (Appendix 3).

4.2 Management implications of changes in fish growth

4.2.1 Yield

Losses of fishing yield are commonly associated with declining numbers of fish, either due to stock collapse (less fish in a particular fishing ground), or to changes in distribution (fish moving away from a particular fishing ground) which have been recently documented in many ecosystems (see Section 3.1). In contrast, the impact of changes in fish growth on fishing yield (same number of fish, but individuals smaller in size) has received comparatively little attention. The decline in body size observed in North Sea fish species (see Section 4.1.2) has been estimated to result in an average loss of yield of 23%, with losses up to 48% of one species (Table 4). Although these figures were obtained through crude approximations (see Baudron et al., 2014), they illustrate the potential scale of the problem: growth change could result (and, most likely, already have) in significant yield losses irrespective of fish stock abundance (number of fish). In addition, changes in growth could also have further indirect implications for fishing yield such as loss of reproductive potential (smaller fish lay fewer and smaller, less viable eggs) or changes in trophic interactions (sizes of predators and preys). As seafood is increasingly contributing to the worldwide supply of protein, the implications of fish growth changes on fishing yield should no longer be ignored.



Substock	YPR 1978	YPR 1993	Individual yield loss	% loss
Haddock North	0.00473	0.00290	0.00183	38.7
Whiting North	0.00089	0.00086	0.00003	3.1
Whiting South	0.00116	0.00060	0.00056	48.1
Herring North	0.00514	0.00450	0.00063	12.3
N. Pout North	0.00171	0.00133	0.00038	22.2
Sprat South	0.00075	0.00072	0.00003	4.0
Sole male South	0.10458	0.08600	0.01858	17.8
Sole female South	0.14949	0.12571	0.02377	15.9
Plaice male South	0.12375	0.06664	0.05711	46.2
Average				23.1

Table 4. Yield-per-recruit (YPR) values (kg) prior (1978) and after (1993) the observed decline in L_∞, with corresponding individual yield loss in value (kg) and percentage. 1978 and 1993 were years in which the standardized common Trend 1 reached its maximum and minimum values prior and after the decline in L_∞.

For short-lived species, e.g., squid, climate-driven changes in growth can rapidly change the size structure of the population which can quickly change the interpretation of CPUE (Pecl et al. 2004). In some years individual squid (*Sepioteuthis australis*) weigh 1.2kg in others 0.4kg. This is consequential for CPUE indices which are expressed as kg per day. A constant value of CPUE can vary considerably in the number of individuals that contribute to that value depending on environmental conditions.

4.2.2 Bioeconomics

The bioeconomic implications of growth impacts on fish have been explored for Alaskan fisheries as summarised in two distinct aspects, summarised briefly below.

4.2.2.1 Size-targeting and products in the Bering Sea pollock catcher processor fishery

The standard weight-based quota regulations used to manage most regulated fisheries do not consider the size of individual fish that fill that quota. However, fish of different sizes may present varying profit opportunities and have different impacts on the stock's future growth potential (Asche and Hannesson 2002; Morrison-Paul et al. 2009; Sjoberg 2015, Asche et al. 2015). The links between revenue per unit of quota and the size of individual fish harvested has been investigated for the catcher/processor fleet of the U.S. Bering Sea pollock fishery where larger fish can produce higher-value products. Because price incentives are heterogeneous across vessels, some harvesters profitably chose to target smaller fish to decrease their own harvesting costs. A fisheries manager who controls for the size of fish caught in the pollock fishery could increase estimated profits by more than 10 percent, and while part of the benefit is from higher prices coming from higher-value products, more than 75 percent of the increase in fishery value results from a larger biomass (Chen and Haynie under review).

4.2.2.2 Products, vessels, and trip length in the Bering Sea pollock inshore fishery

Fishermen seek to maximize profits so when choosing where to fish, they must consider interactions among the environment, costs, and fish prices. Watson and Haynie (2018) examined catcher vessels in the U.S. Bering Sea fishery for walleye pollock (2003- 2015) to characterize fisher responses to environmental change (e.g., abundance and water temperature). When pollock were abundant and water was warm, the fleet fished in similar locations. Conversely, when temperatures were cooler or pollock abundance declined, two fishing strategies emerged, depending on the processor where a vessel delivered. One vessel group, whose catches were more likely to become fillets, often made shorter trips, requiring less fuel and time at sea. A second vessel group, whose catches were more likely to become surimi, travelled farther from port, to regions with higher catch rates but generally smaller fish. By fishing in different locations to satisfy different markets, the fleet sustained revenues and buffered against environmental change. This illustrates that a "one vessel fits all" approach may be insufficient for assessing the resilience of fleets to climate change.

4.3 Data available for modelling individual growth rates

The age/length data for many commercial fish stocks around the world offer an unparalleled opportunity to test the impacts of warming temperature on growth rates of individual fish. One aim of the project was to begin working towards a long-term research objective (identified as Manuscript 3 in Section 1.5) *Meta-analysis of the historical changes in fish growth across the globe and identification of putative mechanisms e.g., the temperature-size rule*. Consequently, the workshop reviewed some of the global data resources on age-length over time, a selection of which are summarised in this section. Australia is not included.

4.3.1 European and Nordic databases for analysing growth

4.3.1.1 Europe

The DATRAS database is hosted and maintained by the ICES. It contains fish trawl survey data collected by nations fishing in EU waters. It is publicly accessible at http://www.ices.dk/marine-data/data-portals/Pages/DATRAS.aspx. The database contains a wide range of data such as length frequency, length-at-age, maturity, etc.

The length-at-age data available from DATRAS are structured as age-length keys (ALKs). ALKs are available for five of the surveys included in DATRAS. These survey cover the North Sea, the southern North Sea, the West of Scotland, the Baltic Sea, and the Celtic Sea/Bay of Biscay. The North Sea dataset spans the longest time period: from 1965 to present. Other surveys' ALKs begin in the late 1980s to the mid-1990s (Figure 13).

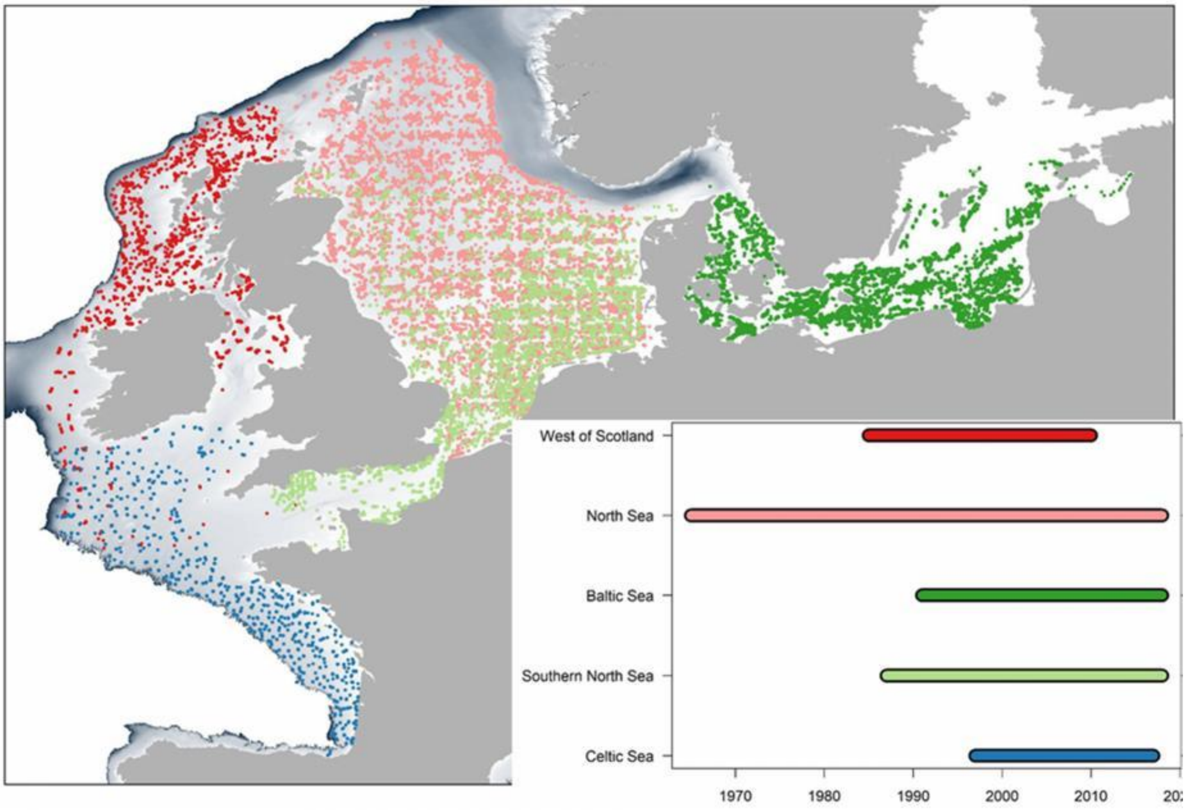


Figure 13. Spatial and temporal coverage of length-at-age data available from DATRAS.

Available ALKs for the Baltic Sea include three species; European flounder (*Platichthys flesus*), European plaice (*Pleuronectes platessa*), and Atlantic cod (*Gadus morhua*). ALKs from the southern North Sea include two flatfish species, European plaice and Common sole (*Solea solea*). ALKs from the North Sea include Atlantic cod, Haddock (*Melanogrammus aeglefinus*), Atlantic herring (*Clupea harengus*), Saithe (*Pollachius virens*), Norway pout (*Trisopterus esmarkii*), Whiting (*Merlangius merlangus*), European plaice, Atlantic mackerel (*Scomber scombrus*), and European sprat (*Sprattus sprattus*). ALKs from the Celtic Sea/Bay of Biscay include Atlantic cod, Whiting, Megrim (*Lepidorhombus whiffiagonis*), Anglerfish (2 species) (*Lophius piscatorius* and *L. budegassa*), European hake (*Merluccius merluccius*) and Atlantic mackerel. ALKs from the West of Scotland include Atlantic cod, Haddock, Saithe, Norway pout, Whiting and Atlantic mackerel.

ALKs are obtained via a grid survey sampling design. Rectangles (unit of the grid) cover the survey areas. Each rectangle contains between one and four sampling stations, and at least one haul of the survey trawl is done in each rectangle. For each haul, the catch is sorted by species. The length of individuals are measured so as to obtain a length frequency distribution, and otoliths are sampled in each length class via stratified sampling. The age is subsequently determined by otolith reading. Age readings are reliable for some species (e.g., cod) but known to be biased in others (e.g., hake). The length-at-age data contained in DATRAS is not corrected for length stratified sampling. To do so ALKs need to be raised by the observed length frequency.

4.3.1.2 Norway

Survey time series for length at age and weight at age for stocks that fall under Norwegian management start in the 1980s. There is some data for commercial catches generally go somewhat farther back in time. The longest time series are those for Northeast Arctic cod and Norwegian spring-spawning herring, where there are age data from commercial catches going back to the early 1900s. For Northeast Arctic cod and Icelandic cod, there is an ongoing joint project on long-term otolith and bivalve growth chronologies in relations to cod stock dynamics and climate. For the main Barents Sea stocks (cod, haddock, capelin) there is a Norwegian-Russian program for the annual inter-calibration of age estimates which has been in operation since the early 1990s. There are also regular inter-calibration programs for most main stocks in the Norwegian Sea and North Sea. Temperature is generally measured close to each trawl station taken, also there are a number of time series from hydrographical sections.

4.3.1.3 Iceland

All available paper-archived age, length and other biological data from the Icelandic fisheries have been digitally archived at the Marine and Freshwater Research Institute's fish database. In addition, archived otoliths are routinely stored in a physical database. The earliest age and length data for cod go back to the 1930's with annual measurements (mostly commercial samples) exceeding 1,000 fish at minimum per year and with time increasing to above 10,000 per year. Annual samples of herring are available since the 1940's, haddock since the 1950's and saithe since the 1970's. In addition, intermittent samples of less commercially important species have been taken through time. Two scientific groundfish surveys are conducted annually: the spring survey since 1985 and the fall survey since 1996. Age samples for cod, haddock and saithe as well bottom temperature at each station have been taken since commencement of the surveys with increasing number of species being sampled for age determination with time.

4.3.2 US databases for analysing growth

The US has extensive age/length data that resides in regional fisheries centres, as is described for some of the centres below. The east coast databases are not represented here but likely begin in or around 1970.

4.3.2.1 Alaska Region

The Alaska region comprises three separate ecosystems: 1) the EBS; 2) the GOA; and 3) the AI. The major fishery-independent sources for age and length data are 4 series of trawl surveys conducted by the Alaska Fisheries Science Center (AFSC), including the EBS shelf survey (annual, since 1982), the EBS slope survey (biennial, since 2002), the GOA trawl survey (triennial or biennial, since 1981), and the Aleutian Islands (AI) trawl survey (triennial or biennial, since 1980). The EBS shelf survey has a systematic design in which trawls are conducted at fixed locations within a grid, whereas the other three surveys are stratified random surveys. In recent years (i.e., since 2008) the number of species sampled for otoliths has been the largest in the GOA survey (19 – 22 species per year) and the fewest in the EBS slope survey (7-9 species), with intermediate levels in the EBS shelf survey (8-12 species) and the AI survey (14-17 species). These numbers generally represent the presence of species relevant for stock assessments across the various habitats. Many of the major species with long-standing age-structured stock assessments (i.e., gadids, flatfish, rockfish) have otolith collections extending back to the 1980s, whereas collections for minor species may be relatively recent (and may not necessary include otolith aging for all sample years). Historically, otoliths in AFSC trawl surveys were collected with a length-stratified design (i.e., a fixed number was sampled per size bin and geographic area), but recently random sampling designs (i.e., a fixed number is sampled per survey tow) are becoming more common. Environmental data such as temperature and salinity are obtained for each tow.

Fishery-dependent sampling of otoliths has occurred over a similar time-frame and set of species as survey samples via onboard observer sampling, with two exceptions: 1) random sampling (not length-stratified sampling) of otoliths has been employed since 1999; and 2) observer sampling is typically focused on the predominant species in the haul, but sampling protocols have been modified in order to increase the sample size of non-target species. Multiple reads of otoliths are conducted in order to quantify the precision of age estimates. Age validation studies exist for many of the major species using techniques such as tag/recapture, bomb radiocarbon ageing, and isotopes.

4.3.2.2 California Current Ecosystem

Two primary fishery independent surveys have collected groundfish data in the U.S. waters of the California Current (CC) ecosystem. The AFSC triennial shelf survey was conducted between 1977 and 2001, with 1977 considered an experimental year of data collection that is often excluded from analyses. The triennial survey implemented a fixed line transect survey design, extending as far south as Pt. Conception, California. During 1998 the North West Fisheries Science Center (NWFSC) assumed responsibility for the west coast groundfish bottom trawl survey, continuing the pre-existing survey conducted by the AFSC along the U.S. west coast. The NWFSC implemented an annual fixed line transect survey of the continental slope for a portion of the U.S. west coast from 1998 to 2002, expanding to a coast-wide survey during 2002. Major changes to the NWFSC survey were implemented in 2003, essentially starting a new survey time series, and included: 1) encompassing both the continental shelf and slope; 2) extending the survey period; 3) covering the entire U.S. west coast; 4) switching to a random-stratified design; 5) adopting national protocols to standardize the survey; and 6) increasing the number of stations and sampling says. Biological sampling for data used in assessments occurs at two levels: the level of the tow and the level of the individual. For each tow the entire sample is first sorted to species and weighed. A random subsample is used to record the sex and length of individuals from selected species. This survey samples both fishery targeted species and non-target species not present in commercial data sets. Age and length data have been collected from 22 species in the NWFSC annual survey (10 of which were also sampled in the AFSC triennial survey). Surface environmental data are also collected during the survey using sensors mounted on the trawl gear. Finally, the NWFSC also conducts an acoustics survey for Pacific hake, for which age and length data are also available.

Commercial fishery age and length data are available via state-based sampling programs. These are generally port samples without concurrent collection of environmental data. Commercial data needs to be filtered carefully before analysis as not all samples are random, there may be multiple fleets/gear types used to catch the same species, and other considerations. In many cases the time series of commercial ages and lengths are much longer and have much larger samples sizes compared to the NWFSC surveys. Age data generated for NWFSC groundfish survey and commercial samples also have estimates for between reader bias and variability, at a minimum. In some cases age validation studies are also available.

4.3.2.3 Gulf of Mexico

The goal of the National Marine Fisheries Service, Panama City laboratory ageing program is to determine the age frequency, growth and longevity of economically important demersal and pelagic species in the U.S. Gulf of Mexico and U.S. South Atlantic in order to improve precision estimates for stock assessment and inform ecosystem-based modeling approaches. The age and growth program began in the early 1980s in response to mackerel management needs and expanded based on the Gulf of Mexico reef fish management plan in the early 1990s. Ageing structures have been collected and archived for more than 80 species. Because of their economic importance to the region, 9 demersal species and 2 pelagic species have long-term age datasets covering several decades. The demersal species are red snapper (*Lutjanus campechanus*), vermilion snapper (*Rhomboplites aurorubens*), gray snapper (*Lutjanus griseus*), gag (*Mycteroperca microlepis*), red grouper (*Epinephelus morio*), scamp (*Mycteroperca phenax*), yellowedge grouper (*Hyporthodus flavolimbatus*), gray triggerfish (*Balistes capriscus*) and golden tilefish (*Lopholatilus chamaeleonticeps*). King mackerel (*Scomberomorus cavalla*) and Spanish mackerel (*Scomberomorus maculatus*) are the pelagic species from which samples are collected.

Ageing structures were collected from fishery dependent and fishery independent landings. Commercial and recreational landings accounted for 63% and 20% of samples respectively. Commercial samples were obtained through representative sampling in proportion to the catch. Catch locations were assigned to a National Marine Fisheries Service statistical grid. Recreational samples were collected by opportunistic dockside sampling in proportion to the catch. Most often only general catch or landing locations were available. Fishery independent samples were collected mainly by reef fish surveys using a stratified random sampling design. Exact catch locations were often recorded for these catches. All species with the exception of gray triggerfish were aged using either whole or sectioned sagittal otoliths. Sections of the first dorsal spine were used to age gray triggerfish since the otoliths are small, fragile and difficult to extract (Allman et al. 2016). Of the 11 species aged, 7 are considered moderately difficult to age. For these species a benchmark average percent error (APE; Beamish and Fournier 1981) of 5% or less is used as an acceptable level of between reader precision. Gray triggerfish, scamp, yellow-edge grouper and golden tilefish are considered difficult to age and an APE of less than 10-15% is considered an acceptable level of precision for these species. Bomb radiocarbon has been used to validate otolith based ages for red snapper (Baker and Wilson 2001; Barnett et al. 2018) gray snapper (Fischer et al. 2005) and yellow-edge grouper (Cook et al. 2009). Lead-radium dating techniques were compared to otolith based ages for golden tilefish and confirmed a longevity of 26 years, however radiometric ages did not confirm otolith based ages for males (Lombardi and Andrews 2015). Annulus formation in dorsal spine sections of gray triggerfish has been validated using oxytetracycline dihydrate marked captive reared individuals.

4.4 Methods of analysing growth data for fish

Growth is a biological process that is understood through a rich and well developed theory. Yet, statistical treatments of growth often do not account for the underlying biological processes, and as a result, may make inappropriate assumptions and estimate implausible parameter values. Moreover, any attempt to link growth to environmental change needs to have biologically-based mechanisms relating growth model parameters to the environment. The von Bertalanffy growth function is based on a mechanistic growth model, where growth is the difference between anabolic and catabolic processes. These processes result in covariation between model parameters such as asymptotic size and growth rate. Models can better be interpreted by recognizing that asymptotic size is itself a derived quantity from rate constants that describe the rate of energy intake versus energy expenditure. Finally, physiologists have a keen understanding of the distinct ways that different types of environmental conditions affect metabolism and therefore growth. Despite this rich theory, some recent analysis of growth trajectories failed to adequately characterize the environment-growth linkage. In the short term, this line of inquiry can be enhanced by being more explicit about model assumptions and justifying these assumptions based on metabolic theory.

4.4.1 State-space models

State-space time series models (Section 4.1.3) have been used to model variation in fish size-at-age in several large marine ecosystems in the north Pacific. A time-series approach (rather than a structural model such as the von Bertalanffy growth function used in Section 4.1.2) was used due to difficulty in modeling annual changes in the length at infinity parameter with most typical fisheries datasets. The types of growth variation includes: 1) initial size variability (i.e., the initial size at young age affects the size at age for rest of your life); 2) cohort variability (i.e., the growth rate depends on the year of birth); and 3) annual variability (i.e., the growth rate differs between years, affecting each cohort similarly within a given year). Simulation testing indicated that these types of growth variation could be correctly identified by the statistical estimation model, however, the estimation model sometimes identified growth variation when it did not exist in the simulated data, indicating a tendency for overfitting. The model was fit to stocks from the 3 large marine ecosystems in the North Pacific: CC, GOA, and BSAI. Annual variability was the most common significant term in the model for the CC and GOA, but initial size variability was the most common for the BSAI (based on both fishery and survey data); application of the model to only the fishery data increased the number of stocks for which the dominant source of growth variation was annual variation.

State-space models incorporate both process errors and observation errors. Considerable work was done to identify factors that can influence observations, including survey vs fishery observations, gear selectivity, type of gear (i.e, trawl, longline, etc.), age reading method, season, depth, and spatial location. These issues may be dealt with by trimming the data to reduce heterogeneity introduced by sampling methods, or by using covariates. Some issues observed in this work which are more generally applicable include: the importance of the spatial scale relevant to growth variation; the assumptions often required in obtaining estimates of the von Bertalanffy parameters (i.e. growth rate and maximum size are negatively correlated); which population segments is growth to vary in (e.g. sets of cohorts, all cohorts within selected years); whether covariates are available that could introduce bias in data sets.

State-space models are also a useful method for determining the effects of environmental correlates (e.g. temperature) on biological processes such as growth and maturation. Using an approach similar to the state-space model of Stawitz et al. (above), Miller et al. (2018) incorporated environmental correlates that are measured with observation errors. The state-space model predicted the environmental covariates along with fish size and weight. Repeated measurements of temperature at sampling stations between 1977 and 1987 on the northeast U.S. shelf allowed development of a reference temperature for each area and sampling time, and temperature records were computed as anomalies from the temperature reference. However, the development of the temperature reference introduces some uncertainty that is taken into account in the state-space model. Observations of fish length and weight are also modelled as a function of process errors and observation errors, and a generalized von Bertalanffy model is used in which the growth rate parameter is modelled in a piecewise manner between successive ages as a function of temperature. The fixed effect parameters are estimated by maximizing the marginal likelihoods while integrating over the environmental covariates (which are treated as random effects) in Template Model Builder software. A series of model were considered, ranging from a null model with no effects of temperature to more complex models where temperature affects each age differently with autoregressive deviations. Simulation modeling indicated large deviations between predicted and observed temperature when variation in growth rates is modelled as only a function of temperature. This is an example of “aliasing” in which the fit of the size data was improved by allowing the estimated temperature to deviate from the observations of temperature (i.e., the estimates of temperature were being influenced more strongly by the growth data rather than the temperature data). Applied to Georges Bank Atlantic cod, bottom temperature explains growth variation in the first year of life. The state-space approach of allowing error in the observations of covariates is a natural approach for modeling the effect of temperature on fish growth. However, allowing for unexplained annual variation in growth (as opposed to attributing it entirely to temperature) is important in order to avoid aliasing and its resultant erroneous parameter estimates.

4.4.2 Dynamic factor analysis

Baudron et al. (2014) used a DFA to investigate changes in growth parameters in North Sea fish (Section 4.1.2). To do so, they first fitted a von Bertalanffy growth model to each species on a cohort basis, thereby assuming that all individuals within a cohort (i.e., born in the same year) would experience similar environmental conditions through life. As a result they obtained time series of von Bertalanffy growth parameters for each species. Since both the asymptotic length (L_∞) and K (the curvature of the growth curve i.e., how fast L_∞ is reached) are highly correlated, investigating only one of these two parameters is sufficient to capture a change in growth trajectories over time. Baudron et al. (2014) chose L_∞ since it is a length, and therefore more representative of a change in body size.

DFA is a time series statistical analysis which purpose is to identify one or several common trends among a set of time series, in order to explain the temporal variation across these time series using the minimum amount of common trends. The equation of the DFA model applied to L_∞ time series as done by Baudron et al. (2014) is as follows:

$$L_{\infty,s}(t) = Z_{1,s}x_{1,t} + \cdots + Z_{i,s}x_{i,t} + a_s + \varepsilon_{s,t}$$

where s is the species, t is the year , xis the common trend, Z is the factor loading, a is the offset, and lastly ε is the error term $\varepsilon_{s,t} \sim MVN(0, R)$ with R being the error covariance matrix.

In their study, Baudron et al. (2014) used the DFA to identify a declining common trend in L_∞ to which the majority of species were positively (factor loading values > 0) and equally (all species has similar values of factor loadings). This declining common trend coincided with the increase in sea temperature observed in the study area, as shown by significant negative correlations. Baudron then repeated the DFA approach on species-specific factors that could also explain a decline in body size (e.g., fishing-induced evolution) and found no common trends. This indicates that the rise in sea temperature is the most likely explanation for the synchronous decline in body size observed across species, consistently with our physiological understanding. It should be noted however that Baudron et al. (2014) did not demonstrate causality between shrinking sizes and warming, but merely proceeded by logical elimination of factors other than sea temperature using DFA. DFA was also used for Australian growth data (Section 4.1.1) illustrating that it can be widely applied.

4.4.3 Linking ocean conditions to growth

General physiological theory can be used to interpret biogeographical patterns (i.e., latitudinal gradients in body size) and temporal changes in von Bertalanffy growth parameters that are often related to temperature. Aquatic ectotherms such as marine fish will attempt to distribute themselves so as to maximize growth performance (Portner and Farrell 2008). Oxygen limitation theory indicates that the maximum body size is obtained when oxygen demand meets oxygen supply. Rising temperatures increase the demand for oxygen while also lowering the supply, resulting in smaller body sizes, which can have subsequent effects on mortality, maturity, fecundity, and recruitment (Cheung et al. 2013a).

Predictions of fish growth can be obtained from the von Bertalanffy growth function, which can be parsed into anabolism (a function of both oxygen and temperature) and catabolism (a function of temperature). Predictions of the percent change in the maximum body weight are consistent with observational data (i.e., North Sea, Mediterranean), and extrapolations of shrinking body size from other aquatic ectotherms to marine fish suggest declines in body size of ~5-10% (Cheung et al. 2013b). Decreased maximum body size also affects growth performance (as indicated by von Bertalanffy growth parameters), which has been observed for Atlantic cod (Cheung et al. 2011). There is a current debate in the literature on the body-size scaling exponent in the anabolism term. Cheung et al. (2013a) used a value of 0.7 for this term, which can be considered an average across fish populations. Bigger and more active fish (such as tuna) would have a larger exponent because they rely on muscle energy to support their active lifestyle (Pauly and Cheung 2017).

The metabolic rates of marine fish will reflect the fluctuating environments they experience, and warming and deoxygenation will affect the frequency in which fish experience physiologically stressful conditions (Pauly and Cheung 2017). These physiological drivers would be expected to result in fish moving to higher latitudes (or deeper water) with warming, which would change the size distributions of fish communities (Cheung et al 2013a). Predictions from a global model indicate declines in assemblage-level body size (from both changes in individual growth and shifting biogeography) between 14% and 24% between 2000 and 2050, which the largest changes in the temperate and tropic regions (Cheung et al. 2013a).

4.4.4 Effects of climate on individual growth variability of fish in the North Pacific Ocean

Annual growth-increment widths measured in marine organism hard structures provide an integrated measure of an animal's growth rate over its life span and when related to environmental variability reveal evidence for a biophysical response. At the individual species or stock level relationships between growth and climate are often weak. However, evidence for a functional response between climate variability and animal growth is strengthened when such a response is seen across diverse taxa under the influence of physical processes in a given ecosystem. In this study, a synthesis of the response between climate variability and growth is presented over diverse taxa in the CC, Alaska Coastal Current (ACC) and the EBS ecosystems. Exactly dated growth increment data were analyzed with hierarchical Bayesian and nonlinear mixed effects methods that modelled growth as intrinsic age- and extrinsic climate-related effects, including SST, coastal upwelling, the Multivariate Enso Index (MEI), and the Pacific Decadal Oscillation (PDO). Rockfish (*Sebastes polyspinis*) growth in the CC system responded positively to upwelling derived production characterized by higher than average growth during years with higher coastal upwelling and cool water (Matta et al. 2018; Figure 14). In contrast, rockfish growth in the ACC responded favorably to a combination of winter mixing followed by strong spring/summer stratification characteristic of increased growth during years with warmer water temperatures and relaxed spring downwelling. The same relationship between growth and the index of PDO and SST was evident for a population of geoduck off the coast of British Columbia, Canada (Helser et al. 2012). Flatfish growth in the ACC and EBS responded positively to an increase in sea surface and bottom temperatures and negatively to the extent of sea ice cover in the Bering Sea. Slope rockfish showed much less growth variability than compared to nearshore rockfish indicating that low frequency growth effects may be more strongly coupled to basin-scale processes such as MEI. These results suggest that biophysical coupling between physical factors and rockfish growth likely occurs at several different spatial and temporal scales. Moreover the approach represents a more general statistical methodology for the analysis of growth increment data because it partitions and estimates both the intrinsic age and extrinsic climate effects on growth variability.

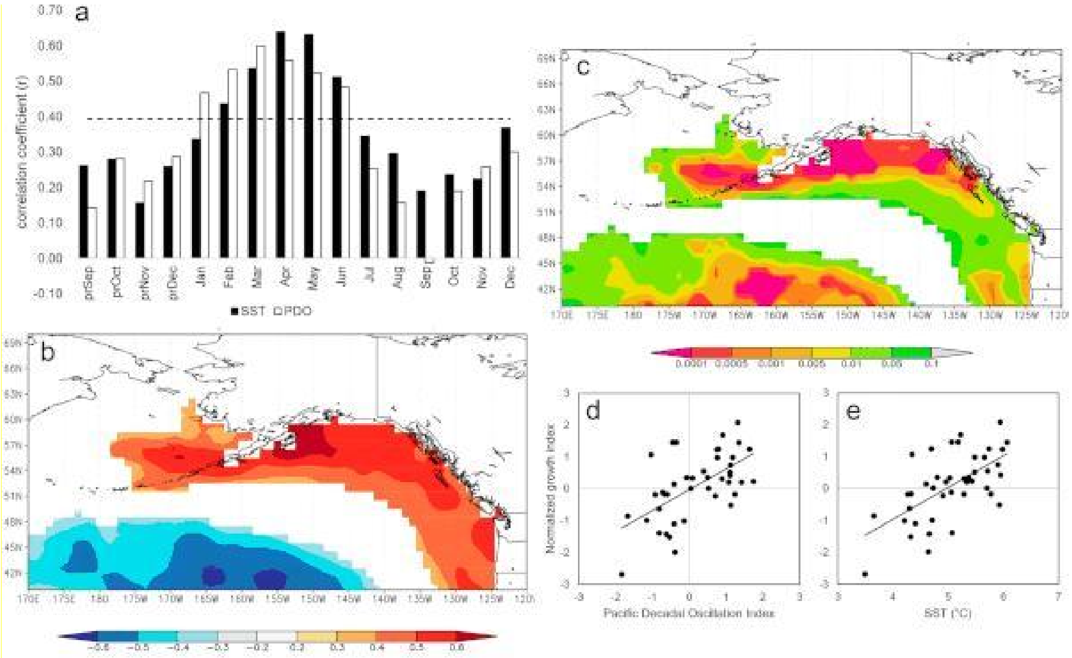


Figure 14. Matta et al. 2018: (a) Correlation coefficients between northern rockfish (*Sebastes polyspinis*) otolith biochronology and monthly values of SST and PDO index, including those from the prior year. Dashed line indicates significance threshold for the correlations ($p < 0.01$). Maps of (b) correlation coefficients (r) and (c) associated p values between gridded SST and the northern rockfish otolith biochronology over the period of 1964–2005. Linear regressions of the northern rockfish otolith index on (d) the PDO and (e) GOA SST for the years 1964–2005

4.4.5 Across-species comparison of growth and body size in marine fish from polar to tropical regions

Marine fish are ectotherms and this means that they typically respond to increasing temperature with faster growth and a reduction in adult body size (Atkinson 1994). This response is observed in acclimation studies and in the field (Atkinson 1994; Forster et al. 2012) and is suggested as one of the main responses of fish to climate warming (Rijnsdorp et al. 2009; Cheung et al. 2012). Yet, the initial physiological response to temperature may not translate directly into a long-term response for at least three reasons: 1) it does not incorporate thermal acclimation and adaptation, 2) it does not take into account that any physiological response to temperature may be modified by changes in ecological dynamics affecting food availability, feeding or activity, and 3) it does not account for changes in the species composition, and hence food-web and coexistence dynamics, of a fish community subject to climate change (e.g. Zhang et al. 2017).

The above processes may favour the initial physiological changes with temperature or may select for a different life-history trait composition (Ohlberger 2013). For example, previous work on temperature in marine fish already showed that at least some cold-water species have growth rates that approach those of temperate and tropical species with a similar ecological lifestyle and of similar body size (Clarke 2003). This shows it is difficult to predict *a priori* whether the changes in growth and body size with temperature (following the temperature-size rule) will be long-lasting. In an attempt to understand this further, van Denderen et al. (*In Review*) examined the effects of temperature on growth and body size in existing fish communities, for which it can be assumed that all processes of selection have already played out. Growth and asymptotic body size were derived from the von Bertalanffy parameters for marine fish across a wide range of habitats (covering a global scale) and ecological lifestyles (hereafter termed guilds, *i.e.* small and large pelagics and demersals, shark/rays and deep-living fish). The results show that the average asymptotic body sizes of fish guilds are constant across temperature. The results further show that the scaling of growth with temperature varies across guilds from largely independent of temperature to strongly positive (see two examples in Figure 15).

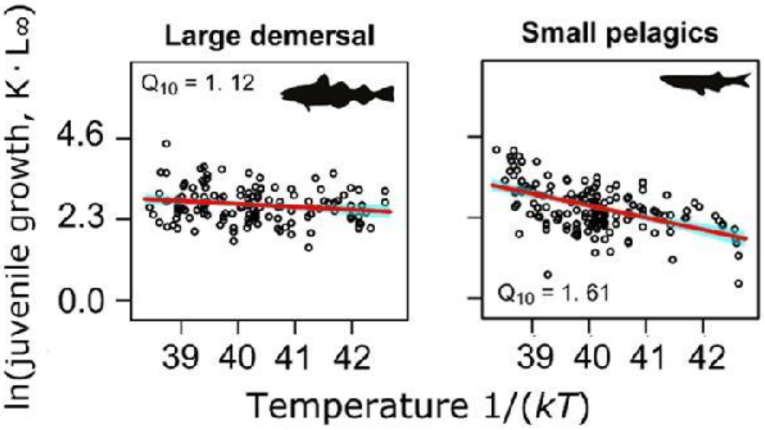


Figure 15. Relationships between fish growth and temperature for large demersals (left) and small pelagics (right). For both groups the temperature is expressed as 1/(kT) for the range ~0-30 °C. Figure from van Denderen et al. (In Review).

These results suggest that many of the changes in growth and body size that are now observed with climate change will not be long-lasting, as there is no indication that faster growth and smaller body sizes are consistently selected for in warmer waters. This indicates that the physiological response to temperature (as predicted by the temperature-size rule and metabolic theory) should perhaps not be used to infer how populations, guilds and communities respond in the longer term or to predict fish production. The long-term response is expected to depend on both physiological limitations and the restrictions set on viable combinations of life-history characters rooted in community assembly and the dynamics of coexisting species.

The processes that affect growth and body size will most likely act on different time scales. In response to temperature change, individuals will initially be affected in their physiological rates and this might change growth and body size following the temperature-size rule. The physiological changes are followed by acclimation that has been observed to occur relatively fast (months) (Seebacher et al. 2014). Species migrations may, in a few generations, reshuffle ecological interactions and the species and trait composition of a community (e.g., Frainer et al. 2017). The effects of evolutionary adaptation in response to temperature will take, in most cases, the most time.

4.4.6 Mixed-effects models

Thorson & Minte-Vera (2016) used a mixed-effects model to conducted a meta-analysis describing the form and magnitude of variation of growth over time of marine fish. The von Bertalanffy model was used, in which the growth rate parameter *k* or the α parameter (i.e., the "condition factor" that scales length to weight) was allowed to vary across years, ages, or cohorts. The deviations were modelled as random effects, whereas the variances on the deviations and the growth model parameters were modelled as fixed effects. The model was fit to weight at age data from 91 marine fish stocks representing 9 families and 25 species; for each species, three treatments of random effects (absent, in k parameter, in α parameter) are possible for each of the age, year, and cohort effects, resulting in 27 models. Evaluation of the models considered three criteria: 1) which model is most parsimonious in explaining the data; 2) the relative magnitude of the age, year, and cohorts effects; and 3) the proportion of variation attributable to any single factor. The variability in the weight-at-age data was explained more parsimoniously by the year effect than by either the age or cohort effects, and the standard deviation of the random effects were largest for the year effects. Most of the weights in the analysis were well below the von Bertalanffy asymptotic weight, so there was little ability to distinguish between *k* and α. Fitting the model to both length-at-age, and weight-at-length, would distinguish between these parameters. This study is an example of the utility of considering not only whether size-at-age has varied over time, but the also the causal mechanisms (i.e., have the temporal changes occurred because of year, age, or cohort effects?). Additionally, the datasets being compiled for our planned analyses are expected to have more contrast in size than those used in Thorson and Minte-Vera and also have observation on both length- and weight- at age, which will help distinguish growth in length from the condition factor.

5 Adaptation to climate change

Adaptation is a central component of managing the impacts of climate change on fisheries. Adaptation can take place on different organisational scales from local communities, to regional fisheries, to high seas and global scales (Miller et al. 2017). At the global scale, the UN's 17 different sustainable development goals (SDGs) serve as guiding principles for evaluating different adaptation strategies. Documented shifts in species distribution (marine and terrestrial) have been linked to defined targets and sub-targets for each of the 17 SDGs (Pecl et al 2017). For example, SDG1, eradicating poverty, is directly impacted by changes in distribution of fish through access to resources, changes in the distribution of pathogens and parasites, and changes in ecological properties of wetlands and coastal areas. Pecl et al. (2017) showed that distributional shifts of marine and terrestrial species interact with almost all of the 17 SDGs but that distributional shifts are not explicitly considered by the targets or sub-targets.

At a national level, National Adaptation Plans (NAPs) aim to reduce vulnerability (Section 1.3) to the impacts of climate change by building adaptive capacity and resilience. As specified by the United Nations Framework Convention on Climate Change, countries that are developing NAPs should: 1) follow a country-specific, gender-sensitive, participatory and fully transparent approach, taking into consideration vulnerable groups, communities and ecosystems; and 2) be based on and guided by the best available science and traditional and indigenous knowledge with a view to integrating adaptation into relevant social, economic and environmental policies and actions.

5.1 Australia

Across Australia there has been a coordinated, cross-sectoral response to developing adaptation programmes for climate change impacts in marine ecosystems that is captured in two documents:

- National Adaptation Research Plan (NARP) for Marine Biodiversity and Resources (https://www.nccarf.edu.au/publications/national-climate-change-adaptation-research-plan-marine-biodiversity-resources-first)
- National Climate Change and Fisheries Action Plan

There has been a particular focus for adaptation in the south-east Australia, which although low in primary productivity like most of the Australian coastline, produces 60% of the country's seafood, where the main species by value is lobster and by volume Australian sardines. Most fisheries are output controlled through quotas, access rights and some degree of spatial management. Most fisheries have some form of co-management (e.g., via stakeholder input on management advisory committees) (Ogier et al 2016), and there is a high participation of public in recreational fishing, boating and diving.

To underpin selection of priorities for adaptation plans a trait-based climate change sensitivity assessment and ranking was undertaken (Pecl et al. 2014). The species designated as most important for the region in terms of ecology and socio-economics, were ranked in terms of sensitivity to climate change, and also categorised as being at risk of range contraction or range extension. Information about high sensitivity to climate change was then used to prioritise species for the development of targeted adaptation strategies. The most sensitive state-based species were identified as abalone and southern rock lobster, blue grenadier was the most sensitive economically important Commonwealth species, and snapper was a medium sensitivity species where some opportunities were anticipated (Pecl et al 2014). Adaptation strategies were then developed for each of these four species by asking: how does climate change intersect with the various components and levels of the fishery management system? The management system was considered to have four levels: operational framework (harvest strategy, stock assessment), fisheries management (management plan, compliance, property-rights, co-management, allocation), fisheries governance (management policy and legislation, ecosystem-based management) and broader marine governance (international obligations, environmental legislation). For each level the impacts of climate change, potential 'levers to pull' in terms of addressing climate change impacts, and barriers to action were identified through a highly participatory process that included multiple workshops to solicit industry knowledge concerning oceanographic, ecosystem or fishery changes. Climate change was put into very localised perspectives by asking industry and managers to identify key stressors. Adaptation options and barriers to implementing the adaptation were then generated by science teams consulting with industry and managers (Figure 16).

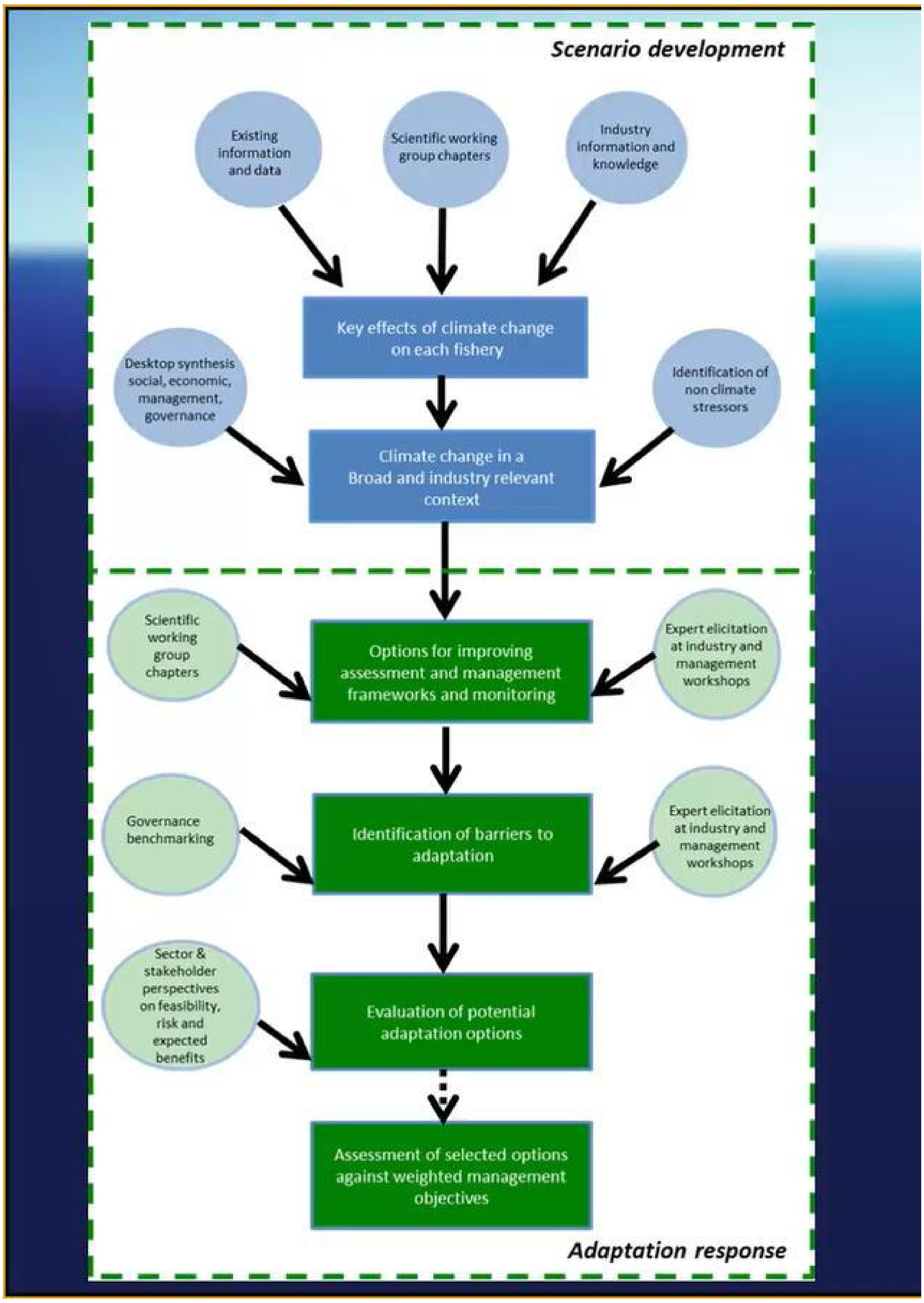


Figure 16. Scenario development and adaptation responses identified for priority fishery species through stakeholder engagement exercises. Figure from Pecl et al. (2014b).

As part of the participatory adaptation workshops, Industry representatives and managers were asked two questions: What can you do? (autonomous adaptations) and What would you like to do but can’t? (potential planned adaptation options that may have barriers preventing responses). They were also asked to consider both short-term (coping) and long-term (potentially transformative) options.

Secondly, fisheries stakeholders were tasked with identifying specific goals for adaption. This exercise required understanding how different stakeholders weight different objectives (e.g., environmental, economic, wellbeing of communities, strengthening management) with aim of seeing how the different adaptation options being proposed would trade-off these defined goals (Jennings et al 2014). Incorporating differential weights (or preferences) of stakeholder groups can identify where there are potential conflicts between adaptation options for fisheries. Implementation details for each adaptation option was summarised, e.g., jurisdiction, differences between jurisdictions, lead time of implementation, cost, who pays, level of controversy. Finally, the scale of the benefits were identified with respect to principal beneficiaries (e.g., fishers, ecosystems). Each adaptation option was then ranked according to feasibility, risk and expected benefits (Pecl et al 2014). An example for adapting to mortality events from thermal shock applied to abalone stocks is given (Figure 17). Optimal adaptations were identified as having low risk (small circles), high feasibility and high benefit. Industry responded favourably to this highly participatory and visual presentation of results.

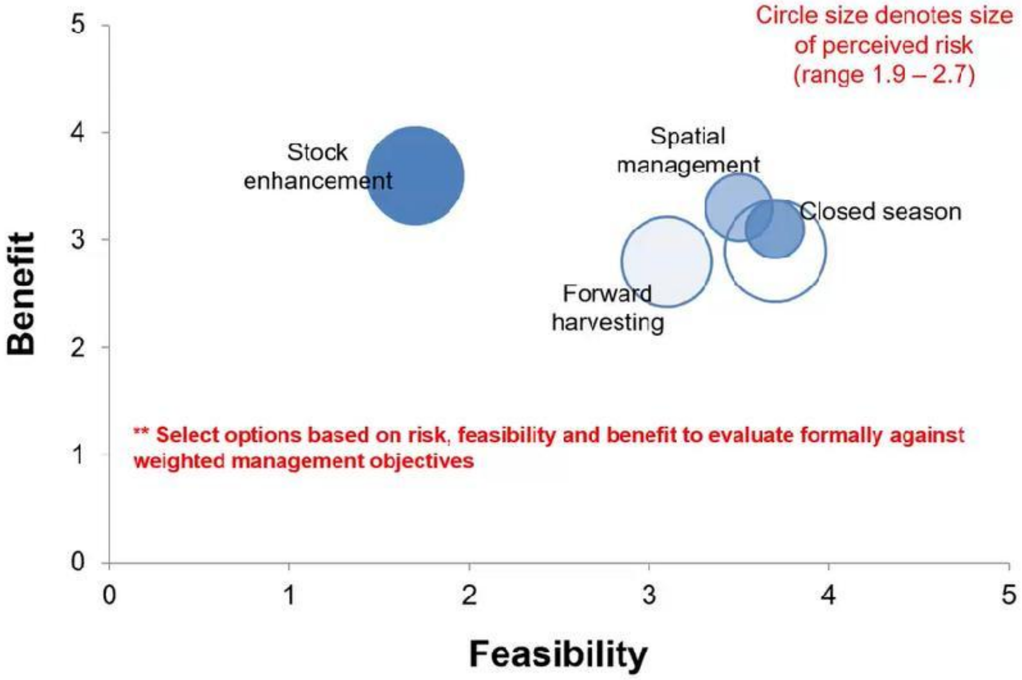


Figure 17. Risk, feasibility and benefit of different adaptation options as determined for the abalone industry in south-east Australia through stakeholder engagements. Circle sizes for each adaptation reflects the magnitude of perceived risk (Pecl et al 2014)

Throughout the process of developing regional adaptation plans input from the fishing industry was critically important. At the start of engagement (2008/2009) 80% of fishers believed that climate change was not happening with the remainder thinking it was happening or “something was up” (Nursey-Bray et al. 2012). By 2016 when the fishing industry was surveyed again there had been a complete reversal. Interviews and surveys suggest this was due to several reasons. Sharp shocks to the environment that had been experienced by fishers including a marine heat wave in 2015 that resulted in mortality of shellfish stocks and outbreaks of disease including paralytic shellfish toxin and a virus causing mortality in Pacific oysters. Over the same time period, a concurrent large-scale “citizen science” engagement process aimed at raising awareness of climate change around Tasmania (Redmap; Section 3.3.5) likely contributed to change in perceptions (Bannon 2016, Nursey-Bray et al 2018).

Many different autonomous adaptations have also been described within different stakeholder groups in Tasmania (Pecl et al in press). These adaptations were characterised using a formal typology (Biagini et al 2014) including: **capacity building**, management and planning, **practice change**, public policy, **information sharing**, physical infrastructure, **warning or observing systems**, green infrastructure and **technology** (options in boldface were most commonly recorded). It is worth considering that the adaptation to climate change is not just about the harvest sector. The entire supply chain (fisher↓processor↓transport↓wholesale/retail↓consumer) must be robust to climate change (Plagányi et al 2014).

Overall, the Australian experience of developing adaptation options can be considered as relatively bottom-up in the sense of being generated through extensive stakeholder engagement exercises, although these have been heavily guided by top-down national plans and the associated investment which effectively directed research effort (Creighton et al 2016). Reflecting on the experience, it is possible to identify several challenges and barriers to adaptation including:

- there are divergent expectations for adaptation research with fisheries management agencies wanting information but not necessarily wanting to commit to while public good funding agencies want management change now;
- stakeholder burnout is an issue because at the regional level there is a limited number of fishers and other stakeholders to call on;
- climate change is not seen as an immediate threat in contrast to other concerns;
- there is a fear of increased costs of adaptation which means that is important to identify opportunities for improving efficiency;
- the time required to undertake interdisciplinary and participatory research is large, even at very localised scales.

5.2 UK

The Climate Change Act 2008 made the UK the first country in the world to have a legally binding long-term framework to cut carbon emissions. The UK has developed a relatively centralised or top-down approach to developing and defining adaptation options both across sectors and across the four home nations (England, Wales, Scotland and Northern Ireland). Across all sectors (not just marine), the UK's ability to adapt to climate change is coordinated through the following activities:

1. a UK-wide CCRA that must take place every five years
2. a NAP which must be put in place every five years to address the most pressing climate change risks. The NAP is the blueprint which guides government action to address the increasing risks from climate change
3. "reporting authorities" (companies with functions of a public nature such as water and energy utilities) prepare reports on how they are assessing and acting on the risks and opportunities from a changing climate.

Information is also reported at the level of UK home nations. For example, the UK CCRA 2017 Evidence Report was also presented as a national summary for Scotland (https://www.theccc.org.uk/tackling-climate-change/preparing-for-climate-change/uk-climate-change-risk-assessment-2017/national-summaries/).

Scotland has its own climate change legislation: the Climate Change (Scotland) Act 2009. Scotland's Climate Change Adaptation Framework (2009) was replaced by Scotland's first statutory Adaptation Programme in May 2014 (Climate Ready Scotland: Scottish Climate Change Adaptation Programme). It is a requirement of the Climate Change (Scotland) Act 2009 that Scottish Ministers report annually on progress on the current Adaptation Programme. For example, the Fourth Annual Report was published in May 2018 (https://www.gov.scot/publications/climate-ready-scotland-scottish-climate-change-adaptation-programme-fourth-annual/pages/5/). The second statutory five-year Adaptation Programme will be published in 2019. The new Programme will address the risks for Scotland set out in the UK Climate Change Risk Assessment 2017 and its Evidence Report Summary for Scotland.

5.2.1 Climate change risk assessment

The second UK- wide CCRA was published in 2017 and was developed through coordinated activities of scientists, government departments and other stakeholders from across the UK. It uses the concept of "urgency" to evaluate each risk with four categories of urgency being defined:

- **More action needed**. New, stronger or different Government policies or implementation activity, over and above that already planned, are needed in the next five years to reduce long-term vulnerability to climate change.
- **Research priority**. Research is needed to fill significant evidence gaps or reduce the uncertainty in the current level of understanding in order to assess the need for additional action.
- **Sustain current action**. Current and planned levels of future activity are appropriate, but continued implementation of these policies or plans is needed to ensure that the risk is managed in the future. This includes any existing plans to increase or change the current level of activity.
- **Watching brief**. The evidence in these areas should be kept under review, with long-term monitoring of risk levels and adaptation activity so further action can be taken if necessary.

In most cases the urgency score is the same for all UK nations because there is insufficient evidence to distinguish among home nations. Many UK fish and fisheries are inherently trans-national resources, therefore it is usually appropriate to coordinate at the UK-level. For UK fisheries, the risks identified in the 2017 CCRA are reported in Natural environment (Ne) category Ne13: *Risks to, and opportunities for, marine species, fisheries and marine heritage from ocean acidification and higher water temperatures*. The overall urgency category assigned to Ne13 was "Research priority" with the justification being: "*More research needed to better understand magnitude of risk to marine ecosystems and heritage*".

5.2.2 National Adaptation Programme

The first UK National Adaptation Programme (UKNAP), published in July 2013, contained a register of actions consisting of actions agreed in the programme for the following themes: Built environment, Infrastructure, Healthy and resilient communities, Agriculture and forestry, Natural environment (Ne), and Business and local government (boldface relevant to marine ecosystems). It aligned the risks identified in the first UK-wide CCRA report to specific actions in the first UKNAP with indicative timescales for each action. The marine actions included many different risks with MA6, the Northward spread of invasive non-native species, being identified as a high order risk. MA4a and MA4b related to distributional shifts and changes in individual growth of fish, respectively. Having identified appropriate actions to address the risk in the 2013 UKNAP, then there was follow-up reporting to evaluate progress towards realising these actions. A report submitted to Parliament in 2017 found that overall (i.e., not specific to marine actions) 51% of actions were assessed as complete and an additional 35% were considered on track or ongoing by those responsible for their delivery.

In 2018 the second UKNAP was published, setting out government's response to the second CCRA and identifying the actions government is proposing to address the risks and opportunities posed by a changing climate over the next five years (Table 5). The actions included focussing on introducing a sustainable fisheries policy as Scotland leaves the CFP and preparing marine plans that include policies specifically aimed at enhancing climate adaptation.

CCRA risk(s) addressed	**Objective**	**Key actions and progress milestones**	**Timing**	**Owner**
Ne13: Ocean acidification & higher water temperature risks for marine species, fisheries and marine heritage	Increase and improve our management of the seas	Introduce a sustainable fisheries policy as we leave the Common Fisheries Policy and prepare marine plans that include policies for climate adaptation		Defra, MMO
		The preparation of ten new Marine Plans for the whole of the English marine area will include horizon scanning to evaluate the potential longer term risks and opportunities from climate change	2021	MMO
		Continue to establish Marine Conservation Zones to contribute to an ecologically coherent network of Marine Protected Areas		Defra
	Ensure productive and extensive seafloor habitats which can support healthy, sustainable ecosystems	Continue to support the Marine Climate Change Impacts partnership		Defra
		Continue to collaborate with selected marine sectors through the "climate smart" working initiative to develop adaptive capacity		MCCIP
		Improve understanding of and responses to climate change impacts on water-borne pathogens and harmful algal blooms		MCCIP working with the Environment Agency, Cefas and the Food Standards Agency

		Continue to support ocean acidification research in order to provide a robust baseline assessment which can be used to examine long-term changes		Defra
	Recover and sustain fish stocks at levels which can produce their maximum sustainable yield	Bring forward the new Fisheries Bill which will ensure sustainable use of fish stocks, a healthy marine environment and a prosperous fishing industry	by 2021	Defra
		Seafish will publish a climate change adaptation report describing the steps industry (fisheries and aquaculture) are taking to respond to climate change, focussing on risks and opportunities associated with climate change in the UK aquaculture sector	by 2023	Seafish
		Continue to produce annual climate change updates for the wild-capture fishing industry	Ongoing	Seafish

Table 5. The actions government is proposing to address the risks and opportunities posed by a changing climate over the next five years with associated time scales (where specified) and owners. From https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/727252/national-adaptation-programme-2018.pdf

5.2.3 Reporting Authority

In 2014 a climate change adaptation report for the UK wild capture seafood industry was produced by Seafish, in collaboration with Cefas and the UK Marine Climate Change Impacts Partnership (MCCIP), for submission to the UK Government under the Climate Change Adaptation Reporting Power[4] (ARP) (https://www.gov.uk/government/publications/climate-change-adaptation-reporting-third-round). These reports are authored by specific industries, or organisations representing industries, to assess current and future predicted effects of climate change on their industry/organisation and their proposals for adapting to climate change. With respect to the latter, these reports can be considered as a bottom-up approach to identifying feasible options. The ARP report (Garrett et al. 2016) considered the major impacts on the fishing industry arising from key climate change drivers and outlined major areas of adaptation action. The ARP exercise comprised a literature review, substantive collaboration with the industry including 15 semi-structured interviews and 3 workshops. It aimed to

---

[4] The Climate Change Act 2008 gives the UK Secretary of State the power of ARP to instruct reporting authorities to reports on what is being done to adapt to climate change.

support the UK seafood industry in developing a managed adaptive approach to climate change. Two specific objectives were identified: i) provide a review of projected climate change impacts with implications for seafood; and ii) identify relevant seafood industry adaptation responses. Five principal climate change drivers were considered: sea level rise; changes in storms and waves; temperature change; ocean acidification; and changes in terrestrial rainfall. Priority risks were identified by ranking risks in terms of confidence, proximity, severity, and possible adaptation actions.

5.2.4 The Economics of Climate Resilience report

In 2013 Defra commissioned the *Economics of Climate Resilience* (ECR) report which included a report on fisheries (Defra 2013). This report gave a detailed assessment of whether or not the UK fishing sector will be able to adapt to the opportunities and threats associated with climate change. Against The adaptive capacity of the fishing industry as a whole was judged to be relatively high partly because it has strong commercial incentives to make the most of profitable opportunities. Furthermore, fishing vessel operators are used to dealing with constantly changing weather and fish stock sizes. However, the ability of some fleet segments (e.g. small vessel operators) to adapt is likely to be more constrained.

The key adaptation actions highlighted in the report included:

- Travelling further to fish for current species, if stocks move away from UK ports, particularly for large pelagic fishing vessels, such as those targeting mackerel and herring.
- Diversifying the livelihoods of port communities, this may include recreational fishing where popular angling species become locally more abundant (e.g. sea bass).
- Enhancing vessel capacity if stocks of currently fished species increase and sufficient quota allows.
- Changing gear to fish for different species, if new or more profitable opportunities to fish different species are available, especially if these are not yet covered by EU quota restrictions (e.g. squid).
- Developing routes to export markets to match the changes in the catch supplied. These routes may be to locations (such as southern Europe) that currently eat the fish stocks that are moving into the UK EEZ.
- Stimulating domestic demand for a broader range of species, through joint retailer and media campaigns.

5.2.5 UK Marine Climate Change Impacts Partnership (MCCIP)

The principle aim of the MCCIP (http://www.mccip.org.uk/) is to provide a co-ordinating framework for the UK scientists to transfer high quality evidence on marine climate change impacts and provide guidance on adaptation to policy advisors and decision-makers. The full MCCIP report synthesises understanding of marine climate change impacts in an accessible and actionable format designed for a target audience of policy advisors, decision makers, Ministers, Parliament and the devolved administrations. The most recent 10-year report card (http://www.mccip.org.uk/impacts-report-cards/full-report-cards/2017-10-year-report-card/) includes a detailed report of impacts on fisheries (http://www.mccip.org.uk/media/1767/2017arc_sciencereview_007_fis.pdf). The Climate Smart Working Reports provide adaptation advice for marine sectors. The Scottish Government contributes funding to the MCCIP with Scottish scientists and industries contributing expertise and advice.

5.2.6 Marine Climate Change Centre (MC3)

Cefas has a large, relatively well-funded research group, MC3, that is specifically dedicated to climate change research (https://www.cefas.co.uk/services/research-advice-and-consultancy/climate-change/). MC3 scientists[5] undertake cutting edge climate research, provide in-depth understanding of the global evidence base, coordinate the current thinking on marine climate change issues generally, investigate gaps in current knowledge and helps the UK to develop a robust response to the challenge of global warming. MC3 also hosts MCCIP (Section 5.2.5). It is worth noting that there is no direct equivalent to MC3 within Marine Scotland – Science that undertakes research focussing on climate change impacts on wild capture fish stocks. The Marine Alliance for Science and Technology for Scotland initiative (https://www.masts.ac.uk/) has twelve research themes, or forums, including fisheries and aquaculture, however, MASTS does not have a dedicated climate change theme.

5.3 US

5.3.1 National overview of adaptation plans

Gregg *et al.* (2016) provides a summary of adaptation actions in the US that are specific to fisheries (both Atlantic and Pacific) and based on interviews with federal, tribal, state and other stakeholders. Commonly used adaptation approaches were organised into four broad categories:

Capacity building: strategies include conducting research and assessments, investing in training and outreach efforts, developing new tools and resources, and monitoring climate change impacts and adaptation effectiveness.

Policy: strategies include developing adaptation plans, creating new or enhancing existing policies, and developing adaptive management strategies.

Natural resource management and conservation: strategies include incorporating climate change into restoration efforts, enhancing connectivity, reducing local change, and reducing non-climate stressors that may exacerbate the effects of climate change.

Infrastructure, planning, and development: strategies include protecting critical coastal infrastructure used by the fishing industry, and creating or modifying coastal development measures to increase habitat resilience.

Based on their review, Gregg et al. (2016) made several reasonably generic recommendations for advancing climate-informed fisheries management over the long term:

- Advance monitoring efforts of climate-driven impacts on species, habitat, and fishing communities.
- Enhance habitat connectivity and areas under protection.
- Reduce non-climate stressors to improve overall resilience of species, habitats and communities to climate change.
- Create flexible multi-species permitting, licensing and management plans. Enabling flexibility in terms of when, where, what and how much is harvested will become increasingly important to sustain fishing livelihoods.
- Adjust quotas to help sustain stocks (e.g. reduce fishing pressure on vulnerable stocks).

---

[5] Two MC3 scientists attended the Aberdeen workshop and contributed to this report (J. Pinnegar and B. Townhill)

- Temporarily close fisheries when necessary. Managers should support rapid response measures to reduce stress on vulnerable stocks, including temporary closures.
- Evaluate potential and establish procedures for new commercial and recreational fisheries (e.g. establishment of catch limits, new permitting procedures).
- Create international cooperative fisheries agreements. Climate change will not be confined by political or social boundaries.
- Diversify fisheries and/or livelihoods. In some areas, climate-induced effects on fisheries may threaten entire communities' livelihoods.

More localised approaches to adaptation planning are available on the Environmental Protection Agency's Adaptation Resource Center (https://www.epa.gov/arc-x) which is an interactive resource to help local governments. Case studies can be selected specific to different areas of interest, level of government and region. There are case studies related to ecosystem protection (https://www.epa.gov/arc-x/ecosystem-protection-strategies-climate-change) including some information related to coastal fish communities. Adaptation plans for large commercial fish stocks are not available in this resource.

5.3.2 Ecosystem-based adaptation planning for Alaskan fisheries

The Alaska Climate Integrated Modeling (ACLIM) project is an interdisciplinary research effort between physical, biological, economic, and social scientists at the NOAA Fisheries AFSC, the NOAA Pacific Marine Environmental Laboratory and the University of Washington. The ACLIM project examines how different climate scenarios are likely to impact the Bering Sea ecosystem to ensure that the Bering Sea management system is ready for these potential changes. ACLIM integrates climate scenarios with a suite of biological models that include different levels of ecosystem complexity and sources of uncertainty. The bio-physical models need to be coupled with models of fisher behaviour and management scenarios. The complexity of the economic models varies to match the scale of the biological models with which they are coupled.

To do this, groups of economic and management factors that are the core drivers of fisheries were identified. For management, there are many possible future policy choices, such as changes in target and bycatch species allocations or expanded spatial protective measures that can reduce the vulnerability of different stakeholders. Building on shared socioeconomic pathways (SSPs), the primary measures that have been demonstrated to impact past fisher behaviour are defined, as well as a range of future economic changes and policy interactions under which future integrated modelling outcomes are predicted. Different policy tools can have a large impact on how effectively management can adapt to environmental change and variation. This approach was compared with the approaches of several other large integrated modelling projects and the specific features of the Bering Sea ecosystem are discussed to highlight the management system that would make such approach the most effective for marine resource management in the North Pacific. Several recent publications are available including Holsman et al. (in press). Hermann et al (in press), and Reum et al. (2019a,b).

5.4 Comparing and contrasting the approaches taken to adaptation planning in Australia, UK and US

Only three countries can be considered to have well developed examples of adaptation plans specific to marine ecosystems: Australia, UK and US. Comparing the three approaches (Sections 5.1, 5.2. and 5.3) is therefore informative particularly because the three countries span a gradient in vulnerability of fisheries to climate change with the UK being at the lower end and Australia being at the upper end of the scale (Allison et al 2009; Blasiak et al. 2017; Ding et al. 2017).

Australia undertook an assessment of the vulnerability of different marine species in south-east Australia to climate change which identified four species as being priorities for developing customised adaptation plans. This approach contrasts with that taken in the UK (the CCRA) which assesses the risk at more aggregated levels of organisation (Table 5) and not a species-specific level. Adaptation planning in the south-east Australia region also developed a systematic process (Figure 16) to guide the stakeholder engagements that underpin the development of adaptation plans. Different options were evaluated by the fishing industry with respect to both their overall feasibility, benefit, and risk to identify optimal options (Figure 17). Other examples of best practice in Australia include considering the robustness of the seafood supply chain to climate change using a semi-quantitative approach that could easily be adapted for use in other systems (Plagányi et al 2014). Furthermore, they have undertaken surveys of attitudes of fishers towards climate change of which there are only very limited examples for the UK (Maltby 2018).

The UK approach to adaptation planning is, by comparison to Australia’s and the US’s, more centralised and systematic across different sectors. There is feedback between the CCRA and the NAPs as illustrated by Table 5. Critically, the specific action points is assigned an owner and progress towards achieving the goal is evaluated at regular (approximately 5 year) intervals and reported to Parliament. One difference with Australia is that adaptation actions are framed for application at the national level. With respect to fishing, this could be appropriate given that UK fisheries are widely distributed and managed internationally. In the UK stakeholder engagement has been a feature of the ARP (Section 5.2.3) but it is probably not as extensive or intensive as might be the case in south-east Australia. The fact that Australian fishers have come to recognise the salience of climate change to their operations likely contributes to this difference.

Adaptation planning for Alaskan fisheries is currently being coordinated across a variety of research groups through ACLIM (Section 5.3.2). The ecosystem modelling capture how different climate scenarios are likely to impact the Bering Sea ecosystem with the overall aim of ensuring that the Bering Sea management system is ready for these potential changes. There is no exactly analogous effort currently for UK fisheries in Scotland although MC3 has modelling capabilities that could be developed.

6 Insights about climate change impacts on fish from comparing Australia, UK and UK

The workshop assembled experts from eight countries that allowed for a broad perspective into the current state of the art. Discussions identified common issues related to preparing for climate change that are outlined in this section and that are widely applicable.

Global evidence of distributional shifts There is now ample evidence of changes in the distribution of marine species occurring worldwide, as shown in Section 3 of this report which details changes observed in Australia, the US and the UK. These changes are generally, but not always, in a poleward direction and/or towards deeper waters and are consistent with the expectation that marine species will relocate to avoid climate-induced increases in sea temperature. These distributional changes have been mainly associated with warming, although the occurrence of density-dependent habitat selection, and the impact of fishing pressure were also noted to affect distribution. Our perception of these distribution change is only as good as the data available to quantify them. In the US and the UK standardised datasets from scientific surveys allow for a systematic assessment of distribution shifts, while in Australia analyses of distribution changes rely on observations form the public and model simulations as proxies. Improving data collection and reporting of fish distribution would contribute towards our understanding of distribution changes of commercial marine species.

Global evidence on changes in individual growth There is limited support for TSR in both Australian and UK waters suggesting that unrecognised, climate-driven declines in yield has likely occurred in commercial fish stocks. Data from the US were more equivocal, but this could partly be a result of the analyses for Pacific fish stocks which growth is likely to be strongly impacted by upwelling. This possibility is well-founded in theory but requires more testing using global databases, as outlined in Section 8.3. Establishing that the TSR has a broad base of support will enable scientists to communicate the risks posed by warming waters to fish, e.g. the industry resistance to the "shrinking fish" message (Figure 11).

Differential vulnerability of fish stocks to climate change Quantitative vulnerability assessments are widely used as a starting point for describing risks and identifying priority stocks for conservation or adaptation measures. A global-scale assessments of the vulnerability of marine resources has found that the overall the vulnerability of UK fisheries resources is small compared to other regions (Allison et al 2009). On more regional scales, the vulnerability analyses for marine species on the Tasmanian coast was valuable for identifying priority commercial stocks.

Vulnerability of fishing industry to storminess. There is some evidence suggesting that the frequency and intensity of storms will increase in the Northeastern Atlantic (Mölter et al. 2016). The vulnerability of fisheries to changes in storminess is unclear at present (Sainsbury et al. 2018). Vulnerability assessments for specific fishing industries, especially offshore industries but also fish farms, could be enhanced by incorporating appropriate measures of exposure, sensitivity and adaptive capacity to storms.

Policy adaptation A research base is developing advocating preparing ocean governance, specifically policy, for the reality of climate-driven shifts in distribution of fish (Pinsky et al 2018). It would be useful to identify the range of policy levers that are available to deal with this problem and summarise global experience. For example, quota swapping at the national and sub-national level is used in a variety of fisheries to balance the distributional shifts of shared stocks.

Economic and structural drivers of adaptation Climate effects on fisheries can be complex because they arise through a combination of different physical, biological and economic mechanisms that may interact with each other (Haynie and Pfeiffer 2012). Different fleets might react differently to these drivers (Watson and Haynie 2018). Scenario modelling using economic data could be used to identify different adaptation pathways specific for different fleets conditioned on the most likely biological impacts identified (changing biogeography, changing growth rate, changing multi-species composition).

Bottom-up versus top-down approaches to adaptation In spite of having only three examples of NAPS that are comparatively well-developed for marine ecosystems it is clear that there are differences to the approaches to undertaking NAPs. In particular, Australia and the UK form a contrast. The NAP in Australia and associated research investment has directed funding towards bottom-up approaches to identifying detailed, feasible and region-specific adaptations, as outlined in Section 5.1, through extensive stakeholder engagement. By contrast the UK takes a centralised approach with the adaptation plans for marine ecosystems conforming to a nationally defined reporting protocol including CCRA. In both cases, it is appropriate that the implementation time frame be specified and the exact nature of follow-up actions for each adaptation options be tracked, as is done in the UK case.

Salience of climate change to the fishing industry In general fishers perceive climate change to operate on time scales that are too long to be of relevance to day-to-day operations. However, the Australian example of the east coast of Tasmania illustrated how quickly the attitude of fishers could change when presented with both first-hand experience of extreme weather events and scientific knowledge that is communicated effectively (e.g., through stakeholder engagements) and directly relevant to the business (e.g., storminess, economic impacts, yields of fish stocks).

Innovation in developing an evidence base for tracking climate change Research vessel surveys are a standardised information about location of fish distribution and growth over time in North American and European waters. Owing to their consistency these data have been widely used in climate change research. The fishing industry generates a wealth of standardised information that has yet to be fully captured by scientists working on climate change. For example, the fishing industry samples regularly enough to generate high frequency information about the timing of seasonal events such as spawning. The use of industry-generated intraseasonal data regarding the landing of cod roe (McQueen and Marshall 2017) and maturity stages of sole (Fincham et al. 2013) have yielded valuable evidence of shifts in spawning times in the North Sea. Innovative approaches in Australia have been developed in part due to data limitations, for example, the citizen science Redmap project.

7 Recommendations relevant to Scottish fishing industry

At the conclusion of the workshop, a plenary discussion focussed on issues pertaining specifically to Scottish fish and fisheries. Knowledge gaps that were identified by the group fell into two categories: biological knowledge gaps (Section 7.1.1) and industry-focussed knowledge gaps (Section 7.1.2). Within each category the knowledge gaps are listed in descending order of priority (approximate). Barriers to knowledge development and exchange (Section 7.2) and the public outreach required to raise awareness across the Scottish industry (Section 7.3) were also briefly considered.

7.1 Knowledge gaps

7.1.1 Biological knowledge gaps

Greater understanding of the likely impacts of climate change on future fish yields in the North Sea. Baudron et al. (2014) showed that the majority of commercial stocks studied (6 of 8) have already shown substantial decreases in maximum body size that has already led to substantive declines in yields (>20% on average). The next logical step is to project this biological knowledge forward over time to estimate the magnitude of temperature-driven declines in yield in future using the latest projections of ocean conditions (https://www.metoffice.gov.uk/research/collaboration/ukcp/about).

Vulnerability assessments for different species Trait-based vulnerability assessments have emerged as a relatively rapid assessment procedure in which investigators consider how species-specific biological traits underpin the response to climate exposure (Garcia et al. 2014). Climate vulnerability assessments have been increasingly applied to assist in the sustainable management of harvested marine fish and invertebrate populations (Pecl et al. 2014; Hare et al. 2016, Ortega-Cisneros et al 2018). These studies can provide necessary information for policy makers to increase the adaptive capacity of industries affected by climate change (Colburn et al., 2016). On more regional scales, Australia undertook a regional vulnerability analysis of species across south-east Australia and was consequently able to identify four species that were priorities. Adaptation plans for each of these priority species were then developed which represents a rational deployment of limited research capacity. To inform the adaptation planning process for Scottish fisheries it would be useful to undertake a trait-based vulnerability assessment of the marine communities on the west coast and in the North Sea to identify priority species and stocks.

Impacts of ocean acidification Acidification impacts on Scottish shellfish are understudied relative to other shellfisheries globally. This research could synthesise both vulnerable species and vulnerable life history stages. Capture temporal trends in acidification of Scottish waters to gauge whether the magnitude of change is of concern.

Thermal and migratory experience of mobile fish species In order to link changes in distribution to the individual fish thermal experience, it would be helpful to use technology such as otolith increment analysis (Ong et al. 2015) or Data Storage Tags (Neat et al 2014) to reconstruct the thermal experience of fish stocks. This would be particularly valuable for fish such as cod that experience diverse environmental conditions throughout their lifetime. Limited tagging work has been done by the Marine Laboratory in the past (Neat et al. 2014) but there is no ongoing work.

Climate impacts on salmon Insights into the impacts of climate change for recreational fish in Scotland (principally Atlantic salmon) could also provide useful indication of climate change impacts on body size (Todd et al. 2011) and the timing of returns (Juanes et al. 2004). The physiological impacts of climate change on anadromous fish will be similar in several respects and could confirm the nature of likely impacts on catadromous fish.

7.1.2 Industry-focussed knowledge gaps

Historical data describing distribution of fish catches Research undertaken by MC3 illustrated how historical data could be used to describe temporal patterns on where, when and how much fish catch occurred in the North Sea. This generated spatial time series of commercial catch per unit effort data from 1913 which depicted historical trends in the spatial distribution of commercial fish (Engelhard et al. 2011). Government and marine research institutes have collections of either paper records or scans of data relating to catch history or fisheries independent surveys that both can aid in providing a longer time series of relevant data on commercially important species. Specifically, the Marine Laboratory in Aberdeen holds records of surveys going back to the 1920's. Most of these records are scanned, but not fully digitised to a usable and quality controlled data format. There is a possibility to prioritise the digitisation, quality checks, and publication of this data either as a dedicated project to work through the data, where original documents are scanned. This will maximise the use of Scottish historical data in a way that is complementary to the analysis of Cefas data by MC3.

Informing the fishing industry about impacts of climate warming There is a need for readily accessible information about climate change that is customised according to the interest and needs of the industry and that was updated regularly to reflect developments in both local and global knowledge. This would benefit the exchange of knowledge between scientists and the fishing industry. The MCCIP "report card" approach (http://www.mccip.org.uk/impacts-report-cards/) targets specific audience (policy makers and politicians) but could be adapted specifically for an industry audience. Seafish has considerable expertise in communicating with industry on this topic. However, their efforts would benefit from including biological and ecological knowledge such as that reviewed in this report.

Surveying industry perceptions about climate change Implementing adaptation plans presumes industry recognises the need to adapt. This is not necessarily the case in Scottish fisheries. The pelagic industry has been most proactive on the issues of climate change, partly as a consequence of having recent experience of markedly changing resources (mackerel distribution). Overall, there is relatively limited information about attitudes of fishers to climate change and their perceptions of risk. Surveys of different Scottish fleets would be useful, similar to what has been done on a limited scale for the mixed fishery in south-west of England (Maltby 2018). It would be useful to survey fishers having decadal scale experience of fishing so as to assess whether there is direct experience of shifting distribution. It would also be useful to gauge attitudes towards climate change, e.g. Australia. The Maltby thesis also relevant. The interest of fishers for long-term issues such as climate change is often superseded by short-term, more pressing issues such as the landings obligation, resulting in climate-related issues being often relegated to the background. This could be part of activities undertaken by Seafish in order to deliver the climate change adaptation report by 2023 (Table 5).

Preparing for new fishing opportunities Emerging species such as squid, small pelagics and bluefin tuna will potentially become major new resources for the fishing industry. Some, including squid, have in the past been regarded as a supplementary source of income rather than a primary source of income. Managing these emerging resources sustainably and efficiently will require new scientific information and adaptation planning by the Scottish industry around an unstable resource having a short life-span. Management measures would need to be introduced to ensure sustainable harvesting to avoid boom and bust cycles as well as undesirable ecological consequences. Bursaries could be used to allow the industry (fishers and processors) to acquire relevant training.

Vulnerability of seafood supply networks Sensitivity analyses can be used to illustrate how different points in seafood supply chain are differentially impacted by directional changes in climate. For example, increased storminess would impose difficulties in transport of material by land or sea, reduced safety at sea and or less time spent fishing. The Supply Chain Index (Plagányi et al 2014) identifies critical elements as being those elements with large throughput rates, as well as greater connectivity (analogous to a food web). The sum of the scores for a supply chain provides a single metric that approximates both the resilience and interconnectedness of a supply chain. Identification of key elements across the supply chain can assist in informing adaptation strategies to reduce anticipated future risks posed by climate change.

Economic impacts of climate change for Scottish fisheries. Following examples for the Alaskan fisheries (e.g., Watson and Haynie 2018), it would be useful to specifically incorporate knowledge specific to Scottish fisheries, e.g., changing distribution of pelagics or changing individual growth rates (smaller adult body sizes) into bioeconomic models to examine the impacts various scenarios related to changing biogeography, changing species composition of catch (e.g., increase in small pelagics, decline in cod), increased costs due to longer distance trips or increased storminess (see above).

7.2 Barriers to knowledge development and exchange

One key insight was the importance of having a dedicated research group to coordinate and deliver the knowledge required for assessing risk and developing regional adaptation plans. This group could operate at the regional or national scale. In Australia the world-leading research capacity of the University of Tasmania was critically important to coordinating and undertaking many of the key steps including assessing vulnerability and risk and coordinating stakeholder engagement required to identify feasible adaptation options. In the UK MC3 coordinates many of the UK contributions to the CCRA and NAP as well as undertakes basic research resulting in many of the scientific publications referenced here for the North Sea.

Scotland does not currently have a comparable concentration of expertise within a single agency that is dedicated to climate change in marine ecosystems (including fish and fisheries) and that would have the necessary critical mass to coordinate planning and implementation of adaptation activities. There is, however, expertise scattered across universities, government, fishing agencies such Seafish. But being housed in different locations inhibits planning and undertaking a coordinated research programme. Furthermore, there is a lack of enabling funding to define such a programme. This severely constrains the national capacity. The impending loss of EU research funding might have negative consequences for climate change research given that there have been several dedicated EU projects on climate change that has funded Scottish research (e.g., Climefish https://climefish.eu/).

7.3 Raising awareness about climate change in the fishing industry

Climate change is firmly in the public eye due to recent high-level publications and particularly the IPCC report in 2018. As this report highlights (Section 1.2), the Scottish fishing industry's knowledge of climate change is limited and their vulnerability to impacts is largely unassessed. The public event, held as part of this workshop, was very successful because of the involvement of knowledgeable industry participants (George West and Steve Mackinson) speaking alongside scientific experts. One lesson from that experience was that public awareness of climate impacts on marine ecosystems and fish was improved through the direct participation of fishers and other industry voices in public outreach activities. This would diversify the range of stakeholder perspectives voices that are heard by the public beyond the usual scientific viewpoints.

Commercial fish in Scotland are not amenable to “citizen science” initiatives that typically involve leisure activities of the public, for example, recreation fishers and divers (Section 3.3.5). Nevertheless, the fishing industry regularly samples the fish community and marine ecosystem and this sampling is about location of fish in space and time both relevant to climate change research and largely untapped. The move towards self-sampling by the Scottish fishing industry for scientific purposes (often specific to improving stock assessment; see Mackinson et al. 2019) should consider incorporating forms of self-sampling that deliver directly to databases that are accessible for climate change research. This would largely require improvements in both data sharing and data warehousing.

8 Scientific Objectives of the FIS Workshop

The FIS028 proposal had five distinct objectives (Section 1.5):

Manuscript: Worldwide review of empirical evidence of changes in distribution and their causes (**ONGOING**; see Section 8.1);
Manuscript: Worldwide review of empirical evidence of changes in growth and their causes (**ONGOING**; see Section 8.2);
Manuscript: Meta-analysis of the historical changes in fish growth across the globe and identification of putative mechanisms e.g., the temperature-size rule (**ONGOING**; see Section 8.3);
Final project report: the implications for Scottish fisheries will be identified and key knowledge gaps will be identified to inform FIS of future research needs (**COMPLETED**);
Public Event: to share global and local perspectives on the importance of climate change for distribution, productivity and management of commercial fish stocks (**COMPLETED**).

8.1 Manuscript about changes in distribution

An outline of this manuscript was developed at the workshop and subsequently formed the basis of an abstract that was submitted to an international conference titled Species on the Move (http://www.speciesonthemove.com/) being held in South Africa in 22-26 July 2019 (Appendix 2). Prof. Gretta Pecl, a workshop participant from Australia, is co-convenor of the conference. The authorship reflects participants from the FIS workshop. Discussions during the workshop identified the Species on the Move conference as a realistic deadline for having a first draft of the manuscript available for review. The authorship reflects participants from the FIS workshop. FIS will be acknowledged during the presentation and in any resulting publication. We will publish in an open access journal so as to encourage dissemination of the information across the fishing industry.

8.2 Manuscript about changes in growth

Based on the discussions of different growth data and models that took place at the workshop, a workplan for future collaborations was developed along with a team of workshop participants interested in undertaking this research. As a result of this agreement, an abstract was submitted to the ICES Annual Science Conference (http://www.ices.dk/news-and-events/asc/asc2019/Pages/default.aspx) in Sweden from 9-12 September 2019 (Appendix 3). The authorship reflects participants from the FIS workshop. FIS will be acknowledged during the presentation and in any resulting publication. We will publish in an open access journal so as to encourage dissemination of the information across the fishing industry.

8.3 Manuscript on global meta-analysis of fish growth

Subsequent to the workshop, ICES was contacted regarding creating a new international working group dedicated to pursuing the science agenda that the FIS workshop identified as critical to understanding global impacts on fish dynamics. The proposal was positively received by ICES and it was determined that the global scope of the work would make it suitable for a joint working group between ICES and the North Pacific Marine Science Organisation (PICES) (https://meetings.pices.int/). The working group has a tentative title (ICES/PICES WG on climate impacts on life histories and population dynamics) and has been allocated to the ICES Steering Group on Ecosystem Processes and Dynamics (chair: Dr. Silvana Birchenough). ICES was pleased that we already have global representation and a high level of commitment including the FIS workshop participants. Our aim will be to convene a meeting of interested members at the ICES Annual Science Conference in 2019. The creation of a working group is a critical to achieving the goals given for Manuscript 3. FIS will be acknowledged during the presentation and in any resulting publication. We will publish in an open access journal so as to encourage dissemination of the information across the fishing industry.

8.4 Panopto presentations

As described in Section 2.3, the majority of presentations given at the workshop and the entirety of the public event were recorded. These have been converted to MPEG-4 video files and archived offline. Some light editing has been done in order to keep just the content of talks as well as any related discussion, but there is scope for improvement, e.g., including a FIS title page. It is recommended that FIS consider making these files permanently available alongside the final copy of this report on the FIS website.

9 Acknowledgements

All workshop attendees and remote participants (identified in Table 1) are thanked for their contributions to presentations, discussion and this report. A. Audzijonyte, R. Allman, B. Bogstad, C. Champion, T. Essington, M. Haltuch, A. Haynie, T. Helser, E. Hjörleifsson, J. Morrongiello, M. Peck, G. Pecl, J. Pinnegar, M. Pinsky, C. Stawitz, B. Townhill, J. Thorson, and P.D. van Denderen contributed text

to this report. George R. West is thanked for his participation in the public event. Jens Rasmussen assisted in the development of recommendations for future research. The assistance of Mindfully Wired Communications (Harriet Yates and Ginny Russell) is gratefully acknowledged.

10 References

Allison, E.H., Perry, A.L., Badjeck, M.C., Adger, W.N., Brown, K., Conway, D., Halls, A.S., Pilling, G.M., Reynolds, J.D., Andrew, N.L. 2009. Climate change and fisheries: a comparative analysis of the relative vulnerability of 132 countries. Fish and Fisheries 10: 173-196.

Allman, R.J., Fioramonti, C.L., Patterson III, W.F., Pacicco A.E. 2016. Validation of annual growth zone formation in gray triggerfish (*Balistes capriscus*) dorsal spines, fin rays, and vertebrae. Gulf of Mexico Science 1: 68–76.

Asche, F., Chen, Y., Smith, M. D. 2015. Economic incentives to target species and fish size: prices and fine-scale product attributes in Norwegian fisheries. ICES Journal of Marine Science, 72(3), 733–740.

Asche, F., Hanneson, R. 2002. Allocation of fish between markets and product forms. Marine Resource Economics, 17(3), 225–238.

Atkinson, D. 1994. Temperature and organism size: a biological law for ectotherms? Advances in ecological research 25: 1–58.

Audzijonyte, A., E. Fulton, M. Haddon, F. Helidoniotis, A. J. Hobday, A. Kuparinen, J. Morrongiello, A. D. M. Smith, J. Upston, and R. S. Waples. 2016. Trends and management implications of human-influenced life-history changes in marine ectotherms. Fish Fish **17**:1005-1028.

Audzijonyte, A., A. Kuparinen, R. Gorton, and E. A. Fulton. 2013. Ecological consequences of body size decline in harvested fish species: positive feedback loops in trophic interactions amplify human impact. Biol. Lett **9**.

Baker Jr, M.S., and Wilson, C.A. 2001. Use of bomb radiocarbon to validate otolith section ages of red snapper *Lutjanus campechanus* from the northern Gulf of Mexico. Limnology and Oceanography, 46: 1819–1824.

Bannon S. 2015. Citizen Science in a Marine Climate Change Hotspot: A case study on Redmap in eastern Tasmania, Honours Thesis, University of Tasmania.

Barange, M., Bahri, T., Beveridge, M.C.M., Cochrane, K.L., Funge-Smith, S. and Poulain, F., eds. 2018. Impacts of climate change on fisheries and aquaculture: synthesis of current knowledge, adaptation and mitigation options. FAO Fisheries and Aquaculture Technical Paper No. 627. Rome, FAO. 628 pp.

Barnett, B.K., Thornton, L., Allman, R., Chanton, J.P., Patterson III, W.F. 2018. Linear decline in red snapper (*Lutjanus campechanus*) otolith $\Delta^{14}C$ extends the utility of the bomb radiocarbon chronometer for fish age validation in the Northern Gulf of Mexico. ICES Journal of Marine Science, 75(5), 1664–1671

Bates, A.E., Pecl, G.T., Frusher, S., et al. 2014. Defining and observing stages of climate-mediated range shifts in marine systems. Global Environmental Change, 26:27-38.

Baudron, A.R., Needle, C.L., Rijnsdorp, A., Marshall, C.T. 2014. Warming temperatures and smaller body sizes: synchronous changes in growth of North Sea fishes. Global Change Biology 20: 1023-1031.

Baudron, A.R., Fernandes, P.G. 2015. Adverse consequences of stock recovery: European hake, a new “choke” species under a discard ban? Fish and Fisheries, 16: 563–575.

Beamish, R.J., Fournier, D.A. 1981. A method for comparing the precision of a set of age determinations. Canadian Journal of Fisheries and Aquatic Sciences 38: 982–983.

Belkin, I.M. 2009. Rapid warming of Large Marine Ecosystems. Progress in Oceanography 81: 207–213.

Bennet, N.J., Dearden, P., Murray, G., Kadfak, A. 2014. The capacity to adapt? Communities in a changing climate, environment, and economy on the northern Andaman coast of Thailand. Ecology and Society 19(2): 5

Beraud, C., van der Molen, J., Armstrong, M., Hunter, E., Fonseca, L., Hyder, K. 2018. The influence of oceanographic conditions and larval behaviour on settlement success—the European sea bass *Dicentrarchus labrax* (L.). ICES Journal of Marine Science, 75: 455–470.

Biagini, B., Bierbaum, R., Stults, M., Dobardzic, S., McNeeley, S.M. 2014. A typology of adaptation actions: A global look at climate adaptation actions financed through the Global Environment Facility. Global Environmental Change 25: 97-108.

Blasiak, R., Spijkers, J., Tokunaga, K., Pittman, J., Yagi, N., Österblom, H. 2017. Climate change and marine fisheries: least developed countries top global index of vulnerability. PLoS ONE 12: e0179632.

Boyd, R., Roy, S., Sibly, R., Thorpe, R., Hyder, K. 2018. A general approach to incorporating spatial and temporal variation in individual-based models of fish populations with application to Atlantic mackerel. Ecological Modelling, 382: 9–17.

Brown, C.J., O'Connor, M.I., Poloczanska, E.S., et al. 2016. Ecological and methodological drivers of species’ distribution and phenology responses to climate change. *Global change biology*, 22:1548-1560.

Burrows, M.T., Schoeman, D.S., Buckley, L.B., Moore, P., Poloczanska, E.S., Brander, K.M., Brown, C., Bruno, J.F., Duarte, C.M., Halpern, B.S. and Holding, J. 2011. The pace of shifting climate in marine and terrestrial ecosystems. Science, 334(6056): 652-655.

Carpenter, G., Kleinjans, R., Villasante, S., O’Leary, B.C. 2016. Landing the blame: The influence of EU Member States on quota setting. Marine Policy, 64: 9–15.

Champion, C., Hobday, A.J., Tracey, S.R., et al. 2018a Rapid shifts in distribution and high-latitude persistence of oceanographic habitat revealed using citizen science data from a climate change hotspot. Global change biology, 24(11):5440-5453

Champion, C., Hobday, A.J., Zhang, X., et al. 2018b. Changing windows of opportunity: Past and future climate-driven shifts in temporal persistence of kingfish (*Seriola lalandi*) oceanographic habitat within south-eastern Australian bioregions. Marine and Freshwater Research, 70(1), 33-42.

Chen, Y. A., Haynie, A.C. In prep. An empirical examination of size-targeting in the Bering Sea pollock catcher/processor fishery.

Cheung, W.W.L., Dunne, J., Sarmiento, J.L., Pauly, D. 2011. Integrating ecophysiology and plankton dynamics into projected maximum fisheries catch potential under climate change in the Northeast Atlantic. ICES Journal of Marine Science 68(6):1008-1018.

Cheung, W. W. L., et al. 2012. Shrinking of fishes exacerbates impacts of global ocean changes on marine ecosystems. Nature Climate Change, 3:254–258.

Cheung, W.W., Sarmiento, J.L., Dunne, J., Frölicher, T.L., Lam, V.W., Palomares, M.D., Watson, R., Pauly, D. 2013a. Shrinking of fishes exacerbates impacts of global ocean changes on marine ecosystems. Nature Climate Change, 3(3):254-258.

Cheung, W.W.L., Pauly, D., Sarmiento, J. 2013b. How to make progress in projecting climate change impacts. ICES Journal of Marine Science 70(6):1069-1074.

Clarke, A. 2003. Costs and consequences of evolutionary temperature adaptation. Trends in Ecology & Evolution 18:573–581.

Colburn, L.L., Jepson, M., Weng, C., Seara, T., Weiss, J., Hare, J. A. 2016. Indicators of climate change and social vulnerability in fishing dependent communities along the Eastern and Gulf coasts of the United States. Marine Policy 74:323–333

Cook, M., Fitzhugh, G.R., Franks, J.S. 2009. Validation of yellowedge grouper, *Epinephelus flavolimbatus*, age using nuclear bomb-produced radiocarbon. Environmental Biology of Fishes, 86: 461–472.

Creighton, C., Hobday, A.J., Lockwood, M., Pecl G.T. 2016. Adapting management of marine environments to a changing climate – a checklist for to guide reform and assess progress. Ecosystems. 19(2): 187-219

Cucco, A., Sinerchia, M., Lefrançois, C., Magni, P., Ghezzo, M., Umgiesser, G., Perilli, A., Domenici, P. 2012. A metabolic scope based model of fish response to environmental changes. Ecological Modelling, 237: 132-141.

Dankel, D., Haraldsson, G., Heldbo, J., Hoydal, K., Lassen, H., Siegstad, H., Schou, M., *et al.* 2015. Allocation of Fishing Rights in the NEA. Copenhagen. 88 pp.

Dannevig, H., Hovelsrud, G.K. 2015. Understanding the need for adaptation in a natural resource dependent community in Northern Norway: issue salience, knowledge and values. Climatic Change. 135: 261-275.

Daufresne, M., Lengfellner, K., Sommer, U. 2009. Global warming benefits the small. Proc. Natl. Acad. Sci. U. S. A. 106, 12788–93.

Day, P.B., Stuart-Smith, R.D., Edgar, G.J., Bates, A.E. 2018. Species' thermal ranges predict changes in reef fish community structure during 8 years of extreme temperature variation. Diversity and Distributions 201824:1036–1046.

DeAngelis, D.L., Grimm, V. 2014. Individual-based models in ecology after four decades. F1000prime reports, 6: 39.

Defra 2013. Economics of Climate Resilience Final Report. Online. Available from: http://randd.defra.gov.uk/Default.aspx?Module=More&Location=None&ProjectID=18016

Ding, Q., Chen, X., Hilborn, R., Chen. Y. 2017. Vulnerability to impacts of climate change on marine fisheries and food security. Marine Policy 83: 55-61.

Dulvy, N.K., Rogers, S.I., Jennings, S., Stelzenmüller, V., Dye, S.R., Skjoldal, H.R. 2008. Climate change and deepening of the North Sea fish assemblage: a biotic indicator of warming seas. Journal of Applied Ecology, 45: 1029-1039.

EC. 2016. Council Regulation (EU) 2016/72 of 22 January 2016 fixing for 2016 the fishing opportunities for certain fish stocks and groups of fish stocks, applicable in Union waters and, for Union fishing vessels, in certain non-Union waters, and amending Regulation.

Elith, J., Leathwick, J.R. 2009 Species distribution models: Ecological explanation and prediction across space and time. *Annual review of ecology, evolution, and systematics,* 40:677-697.

Engelhard, G.H., Pinnegar, J.K., Kell, L.T., Rijnsdorp, A.D. 2011. Nine decades of North Sea sole and plaice distribution. ICES Journal of Marine Science, 68, 1090–1104.

Engelhard G.H., Righton, D., Pinnegar J.K. 2014. Climate change and fishing: a century of shifting distribution in North Sea cod. Global Change Biology 20:2473-2483.

Fernandes, J.A., Cheung, W.W., Jennings, S., Butenschön, M., de Mora, L., Frölicher, T.L., Barange, M., Grant, A. 2013. Modelling the effects of climate change on the distribution and production of marine fishes: accounting for trophic interactions in a dynamic bioclimate envelope model. Global Change Biology 19(8): 2596-2607.

Fincham, J.I., Rijnsdorp, A.D., Engelhard, G.H. 2013. Shifts in the timing of spawning in sole linked to warming sea temperatures. J. Sea Res. 75:69-76.

Fischer, A.J., Baker, M.S. Jr., Wilson, C.A., Nieland, D.L. 2005. Age, growth, mortality, and radiometric age validation of gray snapper (*Lutjanus griseus*) from Louisiana. Fishery Bulletin, 103: 307–319

Forster, J., Hirst, A.G., Atkinson, D. 2011. How do organisms change size with changing temperature? The importance of reproductive method and ontogenetic timing. Funct. Ecol. 25, 1024–1031.

Forster, J., Hirst, A.G., 2012. The temperature-size rule emerges from ontogenetic differences between growth and development rates Funct. Ecol. 26, 483–492.

Forster, J., Hirst, A.G., Atkinson, D. 2012. Warming-induced reductions in body size are greater in aquatic than terrestrial species. PNAS 109:19310 LP-19314.

Frainer, A., R. et al. 2017. Climate-driven changes in functional biogeography of Arctic marine fish communities. PNAS 114:12202 LP-12207.

Free, C.M., Thorson, J.T., Pinsky, M.L., Oken, K.L., Wiedenmann, J., Jensen, O.P. 2019. Impacts of historical warming on marine fisheries production. Science 363: 979-983.

Garcia R.A., Araujo M.B., Burgess N.D., Foden W.B., Gutsche A., Rahbek C., Cabeza M. 2014 Matching species traits to projected threats and opportunities from climate change. Journal of Biogeography, 41, 724-735.

Garrett, A., Buckley, P., Brown, S. 2016. Understanding and responding to climate change in the UK seafood industry: climate change risk adaptation for wild capture seafood. A joint Seafish/MCCIP report. https://www.seafish.org/media/1476673/climate_change_report_-_lr.pdf

Gregg, R.M., Score, A., Pietri D., Hansen, L. 2016. The state of climate adaptation in U.S. marine fisheries management. EcoAdapt, Bainbridge Island, WA.

Hannesson, R. 2013a. Zonal attachment of fish stocks and management cooperation. Fisheries Research, 140: 149–154.

Hannesson, R. 2013b. Sharing the Northeast Atlantic mackerel. ICES Journal of Marine Science, 70: 259–269.

Hare J.A., Morrison W.E., Nelson M.W., *et al.* 2016. A Vulnerability Assessment of Fish and Invertebrates to Climate Change on the Northeast U.S. Continental Shelf. PLoS One*,* 11, e0146756.

Haynie, A.C., Pfeiffer, L. 2012. Why economics matters for understanding the effects of climate change on fisheries. ICES Journal of Marine Science, 69: 7, 1160–1167.

Helser, T.E., Lai, H., Black, B.A. 2012. Bayesian hierarchical modeling of Pacific geoduck growth increment data and climate indices. Ecological Modelling, 247: 210-220.

Henriksen, T., Hoel, A. H. 2011. Determining Allocation: From Paper to Practice in the Distribution of Fishing Rights Between Countries Determining Allocation. Ocean Development and International Law, 42: 66–93.

Hermann, A. J., Gibson, G.A., Cheng, W., Ortiz, I., Aydin, K., Wang, M., Hollowed, A.B., and Holsman, K. K. in press. Projected biophysical conditions of the Bering Sea to 2100 under multiple emission scenarios. ICES. J. Mar. Sci.

Hirst, D. 2015. Reforming the Common Fisheries Policy (CFP), 2014-20. CBP-05957. London. 19 pp.

Hobday, A.J., Pecl, G.T. 2014. Ocean warming hotspots provide early warning laboratories for climate change impacts. Rev. Fish Biol. Fish. 24, 415–425.

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

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

Holden, M., Garrod, D. 1996. The Common Fisheries Policy: origin, evaluation and future. Fishing News Books Ltd., Oxford, UK.

Holsman, K.K., Hazen E.L., Haynie, A., Gourguet, S., Hollowed, A., Bograd, S., Samhouri, J.F., Aydin, K. in press. Toward climate-resiliency in fisheries management. ICES. J. Mar. Sci.

Horne, C.R., Hirst, A.G., Atkinson, D. 2015 Temperature-size responses match latitudinal-size clines in arthropods, revealing critical differences between aquatic and terrestrial species. Ecology Letters 18: 327–335.

Ianelli, J., Sotwicki, S., Honkalehto, T., MCCarthy, A., Steinessen, S., Holsman, K., Siddon, E., Fissel. B. 2018. Assessment of the walleye pollock stock in the eastern Bering Sea. In Stock assessment and fishery evaluation report for the groundfish resources of the Bering Sea/Aleutian Islands regions.. North Pacific Fishery Management Council, 605 W. 4th Ave, suite 306. Anchorage, AK 99501

ICES. 2016. Report of the Working Group on Fish Distribution Shifts (WKFISHDISH). ICES CM 2016/ACOM:55. 197pp.

Jansen, T., Post, S., Kristiansen, T., Óskarsson, G.J., Boje, J., MacKenzie, B.R., Broberg, M., Siegstad, H. 2016. Ocean warming expands habitat of a rich natural resource and benefits a national economy. Ecological Applications 26: 2021–2032.

Jennings, S., Pascoe, S., Hall-Aspland, S,, Le Bouhelliac, B,, Norman-Lopez, A,, Sullivan, A,, Pecl, G. 2016. Setting objectives for evaluating management adaptation actions to address climate change impacts in south-eastern Australian fisheries. Fisheries Oceanography. 25 (Suppl. 1): 29–44.

Jensen, F., Frost, H., Thøgersen, T., Andersen, P., Andersen, J.L. 2015. Game theory and fish wars: The case of the Northeast Atlantic mackerel fishery. Fisheries Research, 172: 7–16.

Juanes, F., Gephard, S., Beland, K.F. 2004. Long-term changes in migration timing of adult Atlantic salmon (*Salmo salar*) at the southern edge of the species distribution. Can. J. Fish. Aquatic Sci. 61**:** 2392-2400.

Kerby, T.K., Cheung, W.W.L., Van Oosterhout, C., Engelhard, G.H. (2013). Entering uncharted waters: Long-term dynamics of two data limited fish species, turbot and brill, in the North Sea. Journal of Sea Research. 84: 87-95.

Kjesbu, O.S., Righton, D., Krüger-Johnsen, M., Thorsen, A., Michalsen, K., Fonn, M., Witthames, P.R. 2010. Thermal dynamics of ovarian maturation in Atlantic cod (*Gadus morhua*). Can. J. Fish. Aquat. Sci. 67(4): 605-625.

Kooijman S. 2010. Dynamic Energy Budget Theory for Metabolic Organisation. Cambridge, UK: Cambridge Univ. Press

Kristiansen, T., Stock, C., Drinkwater, K.F., Curchitser, E.N. 2014. Mechanistic insights into the effects of climate change on larval cod. Global Change Biology, 20: 1559-1584.

Last, P.R., White, W.T. Gledhill, D.C., Hobday, A.J., Brown, R. Edgar, G.J., Pecl, G. 2011. Long-term shifts in abundance and distribution of a temperate fish fauna: a response to climate change and fishing practices. Global Ecol. Biogeogr. 20: 58–72.

Law, R. 2000. Fishing, selection, and phenotypic evolution. Ices Journal of Marine Science **57**:659-668.

Lenoir, S., Beaugrand, G., Lecuyer, É. 2011. Modelled spatial distribution of marine fish and projected modifications in the North Atlantic Ocean. Global Change Biology, 17: 115-129.

Ling, S. 2008. Range expansion of a habitat-modifying species leads to loss of taxonomic diversity: A new and impoverished reef state. Oecologia, 156:883-894.

Ling, S.D., Johnson, C.R. , Frusher, S.D., Ridgway, K.R. 2009a. Overfishing reduces resilience of kelp beds to climate-driven catastrophic phase shift. PNAS 106: 22341-22345. https://doi.org/10.1073/pnas.0907529106

Ling, S., Johnson, C., Ridgway, K., et al. 2009b. Climate-driven range extension of a sea urchin: Inferring future trends by analysis of recent population dynamics. Global Change Biology, 15:719-731.

Lombardi, L.A., Andrews, A.H. 2015. Age estimation and lead-radium dating of golden tilefish, *Lopholatilus chamaeleonticeps*. Environmental Biology of Fishes, 98: 1787–1801.

MacCall, A.D. 1990 Dynamic geography of marine fish populations. Washington Sea Grant Programme, University of Washington Press, 153 pp.

Mackinson, S., Martin-Gonzalez, G., Balestri, E., Coull, K., Clarke, E., Marshall, C.T. 2019. Feasibility study into a scientific self-sampling programme for the pelagic sector. Fisheries Innovation Scotland project FIS020 report. 110 pages.

Maltby, K. 2018. Projections and perceptions: using an interdisciplinary approach to explore climate change impacts on south-west UK fisheries. A PhD submitted to the University of Exeter. 332 p.

Marras, S., Cucco, A., Antognarelli, F., Azzurro, E., Milazzo, M., Bariche, M., Butenschön, M., Kay, S., Di Bitetto, M., Quattrocchi, G., Sinerchia, M., Domenici, P. 2015. Predicting future thermal habitat suitability of competing native and invasive fish species: from metabolic scope to oceanographic modelling, Conservation Physiology, 3(1): cou059.

Marzloff, M. P., Melbourne-Thomas, J., Hamon, K. G., Hoshino, E., Jennings, S., van Putten, I. E., Pecl, G. T. 2016. Modelling marine community responses to climate-driven species redistribution to guide monitoring and adaptive ecosystem-based management. Glob Change Biol. doi:10.1111/gcb.13285

Matta, M.E., Helser, T.E., Black, B.A. 2018. Intrinsic and environmental drivers of growth in an Alaskan rockfish: an otolith biochronology approach. Environmental Biology of Fishes, 101, 11: 1571–1587

McQueen, K., Marshall, C.T. 2017. Shifts in spawning phenology of cod linked to rising sea temperatures. ICES J. Mar. Sci. 74: 1561–1573.

Miller, T.J., O'Brien, L., Fratantoni, P.S. 2018. Temporal and environmental variation in growth and maturity and effects on management reference points of Georges Bank Atlantic cod. Canadian Journal of Fisheries and Aquatic Sciences, 2018, 75(12): 2159-2171

Molinos, J.G., Halpern, B. S., Schoeman, D.S., Brown, C.J., Kiessling, W., Moore, P.J., Pandolfi, J.M., Poloczanska, E.S., Richardson, A.J., Burrows, M.T. 2016 Climate velocity and the future global redistribution of marine biodiversity Nature Climate Change 6: 83–88.

Mölter, T., Schindler, D., Albrecht, A.T., Kohnle, U. 2016. Review on the Projections of Future Storminess over the North Atlantic European Region. Atmosphere. 7: 60

Morrison-Paul, C. J. , de Torres, M. O., Felthoven, R. G. 2009. Fishing revenue, productivity and product choice in the Alaskan pollock fishery. Environmental and Resource Economics, 44(4), 457–474.

Morley, J.W., Batt, R.D. and Pinsky, M.L. 2017. Marine assemblages respond rapidly to winter climate variability. Global change biology, 23(7):2590-2601.

Morley, J.W., Selden, R.L., Latour, R.J., Frölicher, T.L., Seagraves, R.J., Pinsky, M.L. 2018. Projecting shifts in thermal habitat for 686 species on the North American continental shelf. PloS one, 13(5): e0196127.

Morrongiello, J. R., P. Sweetman, and R. E. Thresher. accepted. Fishing constrains phenotypic responses of marine fish to climate variability. Journal of Animal Ecology.

Morrongiello, J. R., and R. E. Thresher. 2015. A statistical framework to explore ontogenetic growth variation among individuals and populations: a marine fish example. Ecological Monographs **85**:93-115.

Morrongiello, J. R., R. E. Thresher, and D. C. Smith. 2012. Aquatic biochronologies and climate change. Nat. Clim. Change **2**:849-857.

Mullowney, D., Maillet, G., Dawe, E., Rose, G., Rowe, S. 2016. Spawning delays of northern capelin (*Mallotus villosus*) and recovery dynamics: a mismatch with ice-mediated spring bloom? Prog. Oceanogr. 141: 144-152.

Munday, P.L., Jones, G.P., Pratchett, M.S., Williams, A.J. 2008. Climate change and the future for coral reef fishes. Fish Fisheries 9: 261-285.

Neat, F.C., et al. 2014. Movement of Atlantic cod around the British Isles: implications for finer scale stock management. J. Applied Ecology. 51: 1564-1574.

Neuheimer, A. B., R. E. Thresher, J. M. Lyle, and J. M. Semmens. 2011. Tolerance limit for fish growth exceeded by warming waters. Nature Climate Change **1**:110-113.

Nøttestad, L., et al. 2015. Quantifying changes in abundance, biomass and spatial distribution of Northeast Atlantic (NEA) mackerel (*Scomber scombrus*) in the Nordic Seas from 2007 to 2014. ICES Journal of Marine Science 73:359–373.

Nursey-Bray, M., Pecl, C.T., Frusher, S., Gardner, C., Haward, M., Hobday, A.J., Jennings, S., Punt, A.E., Revill, H., van Putten, I. 2012. Communicating climate change: climate change risk perceptions and rock lobster fishers, Tasmania. Mar. Policy 36: 753-759.

Nursey-Bray, M., Palmer, R., Pecl, G. 2018 Spot, log, map: assessing a marine virtual citizen science program against Reed's best practice for stakeholder participation in environmental management, Ocean and Coastal Management 151: 1-9.

Ogier, E.M., Davidson, J., Fidelman, P., Haward, M., Hobday, A.J., Holbrook, N., Hoshino, E., Pecl, G.T. 2016. Fisheries management approaches as platforms for climate change adaptation: Comparing theory and practice in Australian fisheries. Marine Policy 71: 82-93

Ohlberger, J. 2013. Climate warming and ectotherm body size – from individual physiology to community ecology. Functional Ecology, 27:991–1001.

Olafsdottir, A., Slotte, A., Jacobsen, J., Oskarsson, G., Utne, K., Nøttestad, L. 2016. Changes in weight-at-length and size-at-age of mature Northeast Atlantic mackerel (*Scomber scombrus*) from 1984 to 2013: effects of mackerel stock size and herring (*Clupea harengus*) stock size. ICES Journal of Marine Science 73:1255–1265.

Oliver, E. C. J., J. A. Benthuysen, N. L. Bindoff, A. J. Hobday, N. J. Holbrook, C. N. Mundy, and S. E. Perkins-Kirkpatrick. 2017. The unprecedented 2015/16 Tasman Sea marine heatwave. Nature Communications **8**:16101.

Ong, J.J.L., Rountrey, A.N., Meeuwig, J.J., Newman, S.J., Zinke, J., Meekan, M.G. 2015. Contrasting environmental drivers of adult and juvenile growth in a marine fish: implications for the effects of climate change. Scientific Reports, 5:10859

Ortega-Cisneros, K., Yokwana, S., Sauer, W., Cochrane, K., Cockcroft, A., James, N.C., Potts, W.M., Singh, L., Smale, M., Wood, A., Pecl, G.T. 2018. Assessment of the likely sensitivity to climate change for the key marine species in the southern Benguela system, African Journal of Marine Science, 40:3, 279-292, DOI: 10.2989/1814232X.2018.1512526

Pauly, D., Cheung, W.W.L. 2018. Sound physiological knowledge and principles in modeling shrinking of fishes under climate change. Global Change Biology 24:e15-e26.

Payne, N.L. et al. 2018. Combining abundance and performance data reveals how temperature regulates coastal occurrences and activity of a roaming apex predator. Global Change Biology 24: 1884-1893.

Pecl, G.T., Moltschaniwskyji, N.A., Tracey, S.R., Jordan, A.R. 2014. Inter-annual plasticity of squid life history and population structure: ecological and management implications. Oecologia 139: 515-524.

Pecl, G.T., Ward, T., Briceño, F., Fowler, A., Frusher, S., Gardner, C., Hamer, P., Hartmann, K., Hartog, J., Hobday, A., Hoshino, E., Jennings, S., Le Bouhellec, B., Linnane, A., Marzloff, M., Mayfield, S., Mundy, C., Ogier, E., Sullivan, A., Tracey, S., Tuck, G., Wayte, S. 2014. Preparing fisheries for climate change: identifying adaptation options for four key fisheries in South Eastern Australia. Fisheries Research and Development Corporation, Project 2011/039

Pecl, G.T., Ward, T.M., Doubleday, Z.A., Clarke, S., Day, J., Dixon, C., Frusher, S., Gibbs, P., Hobday, A.J., Hutchinson, N., Jennings, S., Jones, K., Li, X., Spooner, D., Stoklosa, R., 2014. Rapid assessment of fisheries species sensitivity to climate change. Climatic Change 127: 505.

Pecl, G., Ogier, E., Jennings, S., van Putten, I., Crawford, C., Fogarty, H., Frusher, S., Hobday, A., Keane, J., Lee, E., MacLeod, C., Mundy, C., Stuart-Smith, J., Tracey, S. (in press). Autonomous adaptation to climate-driven change in marine biodiversity in a global marine hotspot. AMBIO

Perry, R.I., Smith, S.J., 1994. Identifying habitat associations of marine fishes using survey data: an application to the Northwest Atlantic. Canadian Journal of Fisheries and Aquatic Sciences, 51(3), pp.589-602.

Perry, A.L., Low, P.J., Ellis, J.R., Reynolds, J.D. 2005. Climate change and distribution shifts in marine fishes. Science 308 (5730): 1912-1915.

Pinsky, M.L., Worm, B., Fogarty, M.J., Sarmiento, J.L., Levin, S.A. 2013. Marine taxa track local climate velocities. Science, 341(6151):1239-1242.

Pinsky, M.L., Reygondeau, G., Caddell, R., Palacios-Abrantes, J., Spijkers, J., Cheung, W.W.L. 2018. Preparing ocean governance for species on the move. Science, 360, 1189-1191

Pitt, N.R., Poloczanska, E.S., Hobday, A.J. 2010. Climate-driven range changes in Tasmanian intertidal fauna. Marine and Freshwater Research 61: 963-970.

Plagányi, È.E., et al. 2014. A quantitative metric to identify critical elements within seafood supply networks. PLOS ONE. 9(3): e91833.

Portner, H.O., Farrell, A.P. 2008. Physiology and Climate Change. Science 322 (5902):690-692.

Ramos, J.E., Pecl, G.T., Moltschaniwskyj, N.A., Semmens, J.M., Souza, C.A. Strugnell, J.M. 2018. Population genetic signatures of a climate change driven marine range extension. Scientific Reports 8:9558 DOI:10.1038/s41598-018-27351-y

Reum, J., Blanchard, J.L., Holsman, K.K., Aydin, K., Punt, A.E. 2019 Species-specific ontogenetic diet shifts attenuate trophic cascades and lengthen food chains in exploited ecosystems. Okios DOI: 10.1111/oik.05630

Reum, J., Holsman, K., Aydin, K.K., Blanchard, J., Jennings, S. 2019. Energetically relevant predator to prey body mass ratios and their relationship with predator body size. Ecology and Evolution 9:201–211.

Régnier, T., Gibb, F.M., Wright, P.J. 2017. Importance of trophic mismatch in a winter-hatching species: evidence from lesser sandeel. Mar. Ecol. Prog. Seri. 567: 185-197.

Ridgway, K. R. 2007. Long-term trend and decadal variability of the southward penetration of the East Australian Current. Geophysical Research Letters **34**.

Rijnsdorp, A.D., Peck, M.A. , Engelhard, G.H., Möllmann, C., Pinnegar, J.K. 2009. Resolving the effect of climate change on fish populations. ICES Journal of Marine Science **66**:1570–1583.

Rindorf, A., Lewy P. 2006. Warm, windy winters drive cod north and homing of the spawners keeps them there. Journal of Applied Ecology 43:445-453.

Robinson L.M., Gledhill D.C., Moltschaniwskyj N.A., Hobday A.J., Frusher S.D., Barrett N., Stuart-Smith J.S., Pecl G.P. 2015. Rapid assessment of an ocean warming hotspot reveals "high" confidence in potential species' range extensions. Global Environmental Change. 31: 28-37.

Robinson, L.M., Marzloff, M.P., van Putten, I., Pecl GT, Jennings S, Nicol S, Hobday AJ, Tracey S, Hartmann K, Haward M, Frusher S. 2019. Structured Decision-Making Identifies Effective Strategies and Potential Barriers for Ecosystem-Based Management of a Range-Extending Species in a Global Marine Hotspot. Ecosystems. https://doi.org/10.1007/s10021-019-00358-w

Roff, D. A. 1992. The evolution of life histories; theory and analysis. Chapman and Hall, London.

Shears, N. T., and M. M. Bowen. 2017. Half a century of coastal temperature records reveal complex warming trends in western boundary currents. Scientific Reports **7**:14527.

Rutterford, L.A., Simpson, S.D., Jennings, S., Johnson, M.P., Blanchard, J.L., Schön, P., Sims, D.W., Tinker, J., Genner, M.J. 2015 Future fish distributions constrained by depth in warming seas. Nature Climate Change, 5: 569-573.

Sainsbury, N.C., Genner, M.J., Saville, G.R., Pinnegar, J.K., O'Neill, C.K., Simpson, S.D., Turner, R. 2018. Changing storminess and global capture fisheries. Nature Climate Change 8: 655-659.

Scheffer, M., Bascompte, J., Brock, W.A., Brovkin, V., Carpenter, S.R., Dakos, V., Held, H., van Nes, E.H., Rietkerk, M., Sugihara, G. 2009. Early-warning signals for critical transitions. Nature 461: 53–59.

Seebacher, F., C. R. White, C. E. Franklin. 2014. Physiological plasticity increases resilience of ectothermic animals to climate change. Nature Climate Change **5**:61.

Simpson, S.D., Jennings, S., Johnson, M.P., Blanchard, J.L., Schön, P.J., Sims, D.W., Genner, M.J. 2011. Continental shelf-wide response of a fish assemblage to rapid warming of the sea. Current Biology, 21, 1565– 1570.

Sjöberg, E. 2015. Pricing on the Fish Market — Does Size Matter? *Marine Resource Economics*, 30, 277–296.

Stawitz, C.C., Essington, T.E., Branch, T.A., Haltuch, M.A., Hollowed, A.B., P.D. Spencer. 2015. A state-space approach for detecting growth variation and application to North Pacific groundfish. Canadian Journal of Fisheries and Aquatic Sciences **72**:1-13.

Stoll, J.S., Fuller, E., Crona, B.I. 2017. Uneven adaptive capacity among fishers in a sea of change. PLoS ONE 12: e0178266.

Sunday, J., Pecl, G., Frusher, S., Hobday, A., Hill, N., Holbrook, N., Edgar, G., Stuart-Smith, R., Barrett, N., Wernberg, T., Watson, R., Smale, D., Fulton, E., Slawinski, D., Feng, M., Radford, B., Bates, A. 2015.

Species traits and climate velocity explain geographic range shifts in an ocean warming hotspot. Ecological letters 18(9) DOI: 10.1111/ele.12474

Teal, L. R., Hal, R. , Kooten, T. , Ruardij, P., Rijnsdorp, A. D. 2012, Bio-energetics underpins the spatial response of North Sea plaice (*Pleuronectes platessa* L.) and sole (*Solea solea* L.) to climate change. Global Change Biology, 18: 3291-3305.

Teal, L.R., Marras, S., Peck, M.A., Domenici, P. 2018 Physiology-based modelling approaches to characterize fish habitat suitability: Their usefulness and limitations. Estuarine, Coastal and Shelf Science, 201: 56-63.

Thorson, J.T., Minte-Vera, C.V. 2016. Relative magnitude of cohort, age, and year effects on size at age of exploited marine fishes. Fisheries Research 180, 45–53.

Thorson, J.T., Pinsky, M.L., Ward, E.J. 2016. Model-based inference for estimating shifts in species distribution, area occupied and centre of gravity. Methods in Ecology and Evolution 7(8):990-1002.

Thorson, J.T., Ianelli, J.N., Kotwicki, S. 2017. The relative influence of temperature and size-structure on fish distribution shifts: A case-study on Walleye pollock in the Bering Sea. Fish and Fisheries, 18(6):1073-1084.

Thorson, J.T., 2019a. Guidance for decisions using the Vector Autoregressive Spatio-Temporal (VAST) package in stock, ecosystem, habitat and climate assessments. Fisheries Research 210:143-161.

Thorson, J.T., 2019b. Forecast skill for predicting distribution shifts: A retrospective experiment for marine fishes in the Eastern Bering Sea. Fish and Fisheries, 20(1):159-173.

Thresher, R.E., Koslow J.A., Morison, A.K., Smith D.C. 2007. Depth-mediated reversal of the effects of climate change on long-term growth rates of exploited marine fish. Proc. Nat. Acad. Sci. U.S. 104: 7461–5.

Thresher, R., J. Morrongiello, B. M. Sloyan, K. Krusic-Golub, S. Shephard, C. Minto, C. P. Nolan, F. Cerna, and L. Cid. 2014. Parallel decadal variability of inferred water temperatures for Northern and Southern Hemisphere intermediate water masses. Geophysical Research Letters **41**:1232-1237.

Thresher, R. E., J. A. Koslow, A. K. Morison, and D. C. Smith. 2007. Depth-mediated reversal of the effects of climate change on long-term growth rates of exploited marine fish. Proceedings of the National Academy of Sciences **104**:7461-7465.

Tilzey, R. D. J., and K. R. Rowling. 2001. History of Australia's South East Fishery: a scientist's perspective. Marine and Freshwater Research **52**:361-375.

Todd, C.D., Hughes, S.L., Marshall, C.T., Macleans, J.C., Lonergan, M. E., Biuw, M. 2008. Detrimental effects of recent ocean surface warming on growth condition of Atlantic salmon. Global Change Biology. 14: 1-13.

Townhill, B.L., Pinnegar, J.K., Tinker, J., Jones, M.C., Simpson, S.D., Stebbing, P., Dye, S.R. 2017 Non-native marine species in north-west Europe: developing an approach to assess future spread using regional downscaled climate projections Aquatic Conservation: Freshwater and Marine Ecosystems.

Townhill, B.L., Tinker, J., Jones, M., Pitois, S., Creach, V., Simpson, S.D., Dye, S., Bear, E., Pinnegar, J.K. 2018 Harmful algal blooms and climate change: exploring future distribution changes. ICES Journal of Marine Science, 75: 1882-1893.

Van Denderen, P.D., Gislason, H., Andersen, K.H. in prep. Ecological dynamics determine ectotherm community response to temperature

Van der Kooij, J., Engelhard, G.H. and Righton, D.A. 2016. Climate change and squid range expansion in the North Sea. Journal of Biogeography, 43: 2285-2298.

Van Hal, R., Smits, K., and Rijnsdorp, A.D. 2010. How climate warming impacts the distribution and abundance of two small flatfish species in the North Sea. Journal of Sea Research, 64: 76-84.

Vasilakopoulos, P., Marshall, C.T. 2015. Resilience and tipping points of an exploited fish population over six decades. Global Change Biology 21, 1834–1847

Waples, R. S., and A. Audzijonyte. 2016. Fishery-induced evolution provides insights into adaptive responses of marine species to climate change. Front. Ecol. Environ. **14**:217-224.

Watson, J.T., Haynie, A.C. 2018. Paths to resilience: Alaska pollock fleet uses multiple fishing strategies to buffer against environmental change in the Bering Sea. Can. J. Fish. Aquatic Sci. 75: 1977-1989.

Wernberg, T., Russell, B.D., Thomsen, M.S., Gurgel, C.F.D., Bradshaw, C.J.A., Poloczanska, E.S., Connell, S.D. 2011. Seaweed Communities in Retreat from Ocean Warming. Current Biology 21: 1828-1832.

Woillez, M., Rivoirard, J., Petitgas, P. 2009. Notes on survey-based indicators for monitoring fish populations. Aquat. Living Resour. 22, 155-164.

Woodhead, P. 1964. Changes in the behaviour of the sole, Solea vulgaris, during cold winters, and the relation between the winter catch and sea temperatures. *Helgoländer wissenschaftliche Meeresuntersuchungen*, 1: 328-342.

Zhang, L., Takahashi, D., Hartvig, M., Andersen, K.H. 2017. Food-web dynamics under climate change. Proceedings of the Royal Society B: Biological Sciences 284:20171772.

11 Appendices

11.1 Appendix 1: Description of EU Project CERES - Climate Change and European Aquatic Resources

CERES advances a cause-and-effect understanding of how climate change will influence Europe's most important fish and shellfish resources and the economic activities depending on them. The project is providing new knowledge (data sets valuable for global comparisons) and tools needed to successfully adapt European fisheries and aquaculture sectors in marine and inland waters to anticipated climate change. CERES identifies and communicates risks, opportunities and uncertainties thereby enhancing the resilience and supporting the development of adaptive management and governance systems in these blue growth sectors. CERES strongly supports important European policy goals including self-sufficiency of the domestic supply of fish and shellfish. Information was conveyed on recent project results relevant to this workshop including a literature review and time series analyses of environmental drivers affecting growth, distribution and productivity of European fish and shellfish.

A systematic literature review and gap analysis was conducted on the effects of key abiotic factors (T, pH, O2, S) on the productivity and distribution of 37 of the species most important to European fisheries and aquaculture. The Web of Science review found > 21,000 published papers which were filtered by abstract and title to ~350 papers from which datasets were extracted. on 37 of Europe's most valuable species. The category "inland waters fisheries" included the largest number of species and datasets, followed by cyprinids and cultured rainbow trout. The majority of other studies on finfish was research on seabass and seabream in the Iberian Atlantic region and Mediterranean Sea. Data stemming from studies on shellfish were most abundant in the North Sea and Iberian Atlantic regions. In marine fisheries, most studies were conducted on small pelagics in northern areas (herring, sprat) and Atlantic shelf areas (anchovy, sardine). Work on demersal fish focused on cod in northern areas and hake in southern EU waters. The number of studies on large pelagics (e.g., tuna, dolphinfish) was relatively low but larger than those on squids and shrimps.

Knowledge on potential climate change-related drivers (single or combined physical variables) on several responses (vital rates) across four categories (exploitation sector, region, life stage, species), was considerably unbalanced, including a low number of studies i) examining the interaction of abiotic factors, ii) offering opportunities to assess local adaptation, iii) targeting lower-value species. A meta-analysis revealed that projected warming would increase mean growth rates in fish and mollusks and significantly elevate metabolic rates in fish. Decreased levels of dissolved oxygen depressed rates of growth and metabolism across coherent species groups (e.g., small pelagics, etc.) while expected declines in pH reduced growth in most species groups but increased mortality only in bivalves. The meta-analytical results were substantially influenced by the study design and moderators (e.g., life stage, season). Although meta-analytic tools have become increasingly popular, when performed on the limited available data, these analyses cannot grasp relevant population effects, even in species with a long history of study. We recommend actions to overcome these shortcomings and improve mechanistic (cause-and effect) projections of climate impacts on fish and shellfish.

The presentation also reviewed time series conducted in various European regional seas on fish, fish communities and, in some cases, at the ecosystem level. Time series relevant to this workshop include:

1. Barents Sea Ecosystem: a multifactor analysis and PCA was conducted on a long-term data series (1902-2018). The Barents Sea has changed from cold, low demersal stocks, and high fishing pressure in 1980s to warmer, higher demersal stocks and lower fishing pressure. Results suggest that temperature alone cannot explain trends in cod recruitment between 2000-2016. It is likely that fishing pressure is a second major factor influencing recruitment trends.
2. North Sea Fish Community: Generalised Additive Models (GAMs) were conducted on a time series spanning 1983-2013. Species richness (SR) significantly increased during both winter and summer survey periods and was driven by an increase in more southerly (Lusitanian) species. This increase was associated with increases in winter water temperature, potentially increasing the thermal suitability of the North Sea for these species. Considerable spatial variability (particularly between the southern and northern North Sea was observed.
3. Estuarine-dependent juvenile marine fish in the UK: GAMs were conducted on field data collected between 1960-2016. Six out of the nine studied marine migrant fish species showed significant temporal latitudinal shifts in their distribution, including flounder, dab, whiting, bib, pollack and fivebeard rockling. Northward shifts along the east and west coast of the British Isles were consistent with a shift in climate but the evidence of the effect of climatic variables appears to be very limited.
4. Plaice in the North Sea: Generalised Additive Mixed Models (GAMMs) were conducted on time series of fish sizes reported in commercial catches from 1902-2016. After the 1990's, reduced eutrophication and beam trawling has possibly affected prey availability leading to reduced fish growth. Fishing – increasing until 2000, then strongly decreasing; Climate change and distribution shift – juvenile plaice have shifted further offshore. A individual-based evolutionary model with an integrated nested Laplace approximation (INLA) and GLM has also been calibrated using spatially-explicit, size-based data on the habitat occupation by plaice from 1988-2017. The model correctly captures the distribution of different size classes and will be used for climate projections.
5. Anchovy and sardine in the Bay of Biscay: A DEB-IBM was coupled to a biogeochemical model (POLCOMS-ERSEM) and geostatistical analyses were conducted for the period 2000-2017. The probability of habitats occupied by sardine has decreased in recent years which is unrelated to environmental factors such as T and Chla. A decrease in fish length could be an explanation. For anchovy at low stock size (collapse from 2002 to 2005), local spawning occurred only in southern areas. At high stock levels (> 2010) spawning was more widespread after fishery closure and stock recovery to higher densities. The DEB-model suggested a negative effect of warming and low Chl a on the growth rates of anchovy during the recovery period (2009 to 2015).
6. Anchovy and sardine in the northwestern Mediterranean: GAM results for landings per unit effort from 1974-2016 suggest that the very low productivity levels of sardine and anchovy during the last two decades can be attributed to adverse environmental conditions (e.g. negative phase of the the Western Mediterranean Oscillation Index, increasing water temperature or salinity), coupled with continued, excessive fisheries removals. Age truncation (classes 0, 1+) due to fishing pressure has likely caused low resilience of these stocks to poor environmental conditions.
7. Bluefin tuna in the Eastern Atlantic and NW Mediterranean: Cross correlation and STARS were applied to spawning stock biomass (SSB), recruitment and SST for the time period of 1968-2011. Four regime shifts were identified in SSB whereas three different regime shifts were

identified for recruitment coinciding with those identified for the mean SST in the main spawning area during the spawning season suggesting a negative correlation between temperature and recruitment.

8. Dolphinfish in western Mediterranean: Empirical exploration of historical trends of landings and CPUEs from 1981 to 2015 in the Balearic region and from 1954 to 2015 in the vicinity of Malta suggest a weak relationship between temperature and landings in Balearic Islands and no relationship in Malta for the same time-period. CPUE standardization is ongoing so that trends can be explored quantitatively with respect to environmental drivers.

These historical analyses and information obtained from the literature review have advanced the parameterization of projection models for the biology (reported in March 2019) and the bioeconomics (reported in June 2019) for a variety of fisheries resources. Emphasis was placed on effective, participatory engagement of stakeholders from industry using a variety of methods (e.g. mind mapping based on Bayesian Belief Networks and BowTie analyses). Datasets generated by CERES are available for the global synthesis undertaken in this workshop.

11.2 Appendix 2: Species on the Move abstract (Marshall et al.)

Theme Session 1. **Detection, attribution & prediction of changes in species distributions**

Title - **Challenges in quantifying, interpreting and predicting distributional shifts of marine species**

Tara Marshall, University of Aberdeen, UK

Asta Audzijonyte , University of Tasmania, Australia

Alan Baudron, University of Aberdeen, UK

Curtis Champion, University of Tasmania, Australia

Niall Fallon, University of Aberdeen, UK

Alan Haynie, Alaska Fisheries Science Centre, USA

Melissa Haltuch, Northwest Fisheries Science Centre, USA

Bryony Townhill, Centre for Environment, Fisheries and Aquaculture Science, UK

Pieter Daniël van Denderen, National Institute of Aquatic Resources, Denmark

Gretta Pecl, University of Tasmania, Australia

John Pinnegar, Centre for Environment, Fisheries and Aquaculture Science, UK

Malin Pinsky, Rutgers University, USA

Paul Spencer, Alaska Fisheries Science Centre, USA

Christine Stawitz, University of Washington, USA

Jim Thorsen, Alaska Fisheries Science Centre, USA

Oceans are absorbing approximately 80% of the extra heat and 50% of additional CO2 trapped in the atmosphere and, as a result, have undergone rapid changes in temperature and acidity. The evidence for climate-driven global re-distribution of marine species is growing but often based on the distribution of fish species, many of which are mobile and able to rapidly shift their ranges in response to changing environmental conditions. Standardised surveys are commonly used for inferring spatial distribution, however, there are many examples of species moving beyond the bounds of a survey which then limits our understanding. Additionally, there are often non-climate factors that confound the interpretation of range shifts, e.g. fishing or habitat changes. Quantifying the magnitude and rates of distributional shifts is further complicated by the variety of metrics that are used to describe historical species distributions and then contemporary changes in these distributions. Accurately specifying both the suite of drivers underpinning range shifts and the magnitude of range shifts is essential due to the societal importance of marine species for food, local economies and future projections of commercial fish species. Here, based on a cross-comparison of methodological approaches from a range of globally important marine ecosystems, we make recommendations for appropriate approaches to the collection, analysis and interpretation of data describing the abundance and location of marine species.

11.3 Appendix 3: ICES Annual Science Conference 2019 abstract (Spencer et al.)

ICES CM 2019/L

Assessing the impact of climate-induced warming on fish growth: a comparison of modeling approaches applied to the California current ecosystem

Paul Spencer, Christine C. Stawitz, Alan R. Baudron, Timothy J. Miller, Melissa A. Haltuch, C. Tara Marshall

Oceanographic changes due to climate change can have important implications for fish growth, with potential repercussions on population dynamics, harvest rates, reference points, and choice of fishing locations. Increasing sea temperatures, according to the temperature-size rule hypothesis, should result in smaller adult body sizes. Size-at-age data are available for many commercial fish species in ecosystems exhibiting different warming trends and can be used to formally test this hypothesis. In this study, we apply four different time series models to size-at-age observations from 21 species in the California Current ecosystem. Two models focus on temporal variation in von Bertalanffy (VB) growth parameters: one uses dynamic factor analysis to relate cohort-specific VB growth parameters to environmental covariates, while the other is a state-space VB model in which both covariates and growth parameters are autoregressive processes. The other two models are more empirical in nature: one models cohort-specific size-at-age as an auto-regressive process, while the other estimates trends in size-at-age while accounting for both spatial and spatio-temporal covariations. All models also consider other covariates influencing growth including fishing pressure, population density, and fishery selectivity. Applying these different approaches of varying complexity allows for (i) comparing their efficiency in capturing and explaining growth patterns and (ii) a robust evaluation of warming impact on growth compared to variation induced by other factors. This novel study provides a framework which can be applied to size-at-age data from other ecosystems in order to gain a global perspective on climate change impacts on fish growth and fisheries yields.

Keywords: climate change, fish growth, temperature-size rule, random effects, state-space models, dynamic factor analysis

Contact author: Alan R. Baudron, University of Aberdeen, alan.baudron@abdn.ac.uk

FiS Fisheries
Innovation
Scotland

Scottish Charity Number SC045119

Company Number SC477579

FIS MEMBER ORGANISATIONS

marine scotland

The Scottish Government
Riaghaltas na h-Alba

SFF
SERVICES
LIMITED

Scottish Natural Heritage
Dualchas Nàdair na h-Alba
nature.scot

seafish

Young's
SEAFOOD LIMITED

Sainsbury's

FUNDING
FISH

M&S
EST. 1884