climate change

Scotland's centre of expertise connecting climate change research and policy

Informing Scotland's fisheries policies to be adapted and resilient to climate change and ocean acidification

Molly Thornborrow, Brooke McCluskey, Cemlyn Barlow, Kelly Greener, David Vale, Asimina Voskaki, Alexandria Scott

BMT

April 2024

DOI: http://dx.doi.org/10.7488/era/4430

Executive summary

Aims

Understanding the impacts of climate change on target fish stocks is of critical importance to supporting and future-proofing the fishing industry and marine economy.

This project used a literature review, alongside expert engagement, to discuss the predicted effects of climate change on fish stocks, the likely effects on the Scottish fishing industry and to provide recommendations to fill information deficits and inform policy.

Key findings

The Scottish marine ecosystem and the fisheries it sustains face a dynamic and uncertain future due to a changing climate:

- Climate change and ocean acidification is expected to have ecosystem-level impacts, which will likely result in distribution and ecological changes to key commercial species in Scottish waters.
- As the distributions of commercial species shift geographically, and weather becomes less predictable, fishing grounds increase or decrease in importance.
- Climate change stresses could impact the value and utility of traditional Maximum Sustainable Yield (MSY) assessments, which indicate the maximum quantity of fish that can be caught sustainably.

- Area-based management tools, including single species-protection Marine Protected Areas (MPAs), may become ineffective as conservation and management tools in the long term. This is due to changing distributions, abundances and life histories.
- Limiting the pressure from disruptive fishing methods may increase resilience of inshore ecosystems, such as maerl beds and estuaries, to the impacts of climate change.
- Redistribution of commercial species around Scotland may lead to new opportunities for the industry. However, the supporting network of the industry, such as consumers and supermarkets, needs to work in step to support diversification.
- Ways of strengthening current modelling could be explored. For example, by the factoring in of scenarios such as those relating to ecosystem changes or interactions between increasing temperature and ocean acidification.

Recommendations

Future policies may require increased focus on adaptability and flexibility, to achieve successful management of Scottish fisheries. We propose five steps that will contribute to achieving this.

- **Baseline monitoring**: Further research and data monitoring would build a greater understanding of the impacts of climate change in the region and of the capacity for Scottish fisheries to adapt.
- **Risk assessment**: Risk assessments conducted at a local level would identify the most significant threats to individual fisheries under various climate change scenarios. This would enable local fisheries to identify their level of exposure and vulnerability to climate change, to prioritise adaptive capacity at both ecological and socio-economic levels.
- **Trigger points**: The outputs of modelling and risk assessments could inform a trigger-based approach system for fast implementation and to tackle food availability and security issues. Triggers may be based around ‘tipping points’ identified by risk assessments. Reaching a trigger would activate a pre-determined sequence of actions.
- **Stock assessment and Maximum Sustainable Yield (MSY)**: Factoring climatic and other environmental variables into MSY calculations and stock assessments will likely increase fisheries resilience through increasing the ability to forecast and provide more accurate reference points to inform quotas.
- **Collaboration**: Aligning and coordinating fisheries policy with other policies that may impact fisheries management directly or indirectly (eg MPA management) is important to track the dissemination of knowledge and informed actions and decisions. Relationships alongside international foundations will also help to manage shared seas and fish stocks in partnership. Finally, there is a role for supermarkets, retailers and others in educating consumers as the industry adapts to new target species.

Glossary / Abbreviations table

Abbreviation	Explanation	Abbreviation	Explanation
Boreal	Northern species	MSY	Maximum Sustainable Yield
C	Celsius	Mt	Metric Tonne
CFP	Common Fisheries Policy	NAO	North Atlantic Oscillation
CO_2	Carbon Dioxide	NCMPA	Nature Conservation Marine Protected Area
Eurythermal	Temperature tolerant species	nm	Nautical mile
FMAC	Fisheries Management and Conservation Group	NTZ	No-take zone
FMSY	The rate of fishing mortality consistent with achieving MSY	Phenology	Life events of organisms
GVA	Gross Value Added	RIFG	Regional Inshore Fisheries Group
HAB	Harmful Algal Bloom	SCCAP	Scottish Climate Change Adaption Plan
HPMA	Highly Protected Marine Area	SNAP	Scottish National Adaptation Plan
JFS	Joint Fisheries Statement	SST	Sea Surface Temperature
km	Kilometre	TAC	Total Allowable Catch
Lusitanian	Southern species	TSR	Temperature Size Rule
MCFs	Marine Capture Fisheries	UKCRA3	UK Climate Change Risk Assessment 2022
MPAs	Marine Protected Areas	UKFAs	UK Fisheries Administrations

Contents

1 Introduction

1.1 Background and context

The implications of climate change are already apparent in Scotland's marine environment; warming seas, reduced oxygen, ocean acidification and rising sea levels are affecting marine ecosystems and the impacts are expected to become more frequent and severe in the coming decades (Baudron *et al*., 2020; Stoker *et al*., 2020; Townhill *et al*., 2023). Increased sea temperatures and other impacts, such as increased water acidity and ocean acidification, are predicted to influence fish and shellfish communities and the wider marine community (Cheung *et al*., 2021; Findlay *et al*., 2022). Overall, climate change related impacts are projected to alter the viable habitat for several species and add pressure to target fish populations. Therefore, understanding the impacts of climate change on target fish stocks is of critical importance to supporting and future-proofing the fishing industry and marine economy. As Scotland's fisheries enter a new phase with a renewed focus on responsible and sustainable management, as outlined in the Fisheries Act and Scotland's Fisheries Management Strategy (Scottish Government, 2020), it is essential to develop new policies to ensure that Scotland's fisheries are climate resilient.

1.2 Climate change risks and opportunities

The latest UK Climate Change Risk Assessment (HM Government, 2022) (UKCCRA3) has a Summary for Scotland which identifies sixty-one risks and opportunities from climate change in Scotland. Two of the risks identified to natural environment are particularly relevant to the marine sector and have direct implications for fisheries management in Scotland.

N14

Risks to marine species, habitats and fisheries from changing climatic conditions, including ocean acidification and higher water temperatures, requires action.

N15

Opportunities to marine species, habitats and fisheries from changing climatic conditions.

The Scottish Government has a statutory duty to respond to the risks identified in UKCCRA3, and consequently, there is a requirement to examine the risks posed by climate change to the Scottish fishing industry and the marine habitats on which it depends, and to identify ways to reduce, mitigate and manage these risks.

1.3 Project aims

The Future Fisheries Management Strategy – 2020-2030 (FFM Strategy) has set out the commitment for Scotland to manage responsible and sustainable fisheries into the future (Scottish Government, 2020). Additionally, the Climate Change Committee’s most recent assessment of progress in adapting to climate change in Scotland – Is Scotland climate ready? (2022) – concludes that progress has stalled. It calls for time-bound quantitative targets for accountability with adaptation needed to be embedded across all government activity. It emphasised the role of improved monitoring and evaluation, with some changes in climate-related risks currently not sufficiently known or understood. To inform how adaptation could be incorporated into fisheries policies going forward this research aims to answers five main questions:

1. How will climate change modify the distribution and productivity of key commercial fish species (mackerel, herring, haddock, monkfish (or anglerfish), cod, hake, whiting and saithe)?
2. How will climate change impact the fisheries of these target species and consequently their resilience?
3. How do the projected changes compromise the delivery of policy outcomes to:
    a. Reach Maximum Sustainable Yield (MSY) within a stock;
    b. Implement area-based management tools by application of fisheries management measures for existing Marine Protected Areas (MPAs) and key biodiversity locations outside of these sites; and
    c. Limit inshore activity to current levels?
4. To what extent will distribution shifts provide access to new commercial species for exploitation, and how can this be maximised?
5. How should policy action be designed to not only reduce risk and exposure to risk, but also avoid maladaptation and lock-in?

This research prioritises the development of appropriate climate change monitoring, research, and evaluation objectives which should be included in fisheries management decisions going forward. It also considers what amendments to policies might be required in order to include climate variables into fisheries metrics, and tools to aid adaptation within these policies to support commercial fisheries respond to the risks and opportunities outlined in the Scottish Climate Change Adaptation Programme (SCCAP).

2 Methodological approach

The overall approach in this research follows a three-phase plan using a desk-based literature review, engagement with experts and analysis of the results (Figure 1).

Figure 1: Methodological approach: steps used to conduct study.

The literature review was based on a broad body of peer-reviewed journal articles, government studies, non-governmental organisation reports, and other technical reports. Any sources that met the inclusion criteria were then subject to a robustness check for quality, significance and overall confidence. The review outcome was prioritised according to the following inclusion criteria:

- **Date of publication:** sources published from 2010 onwards were included.
- **Topic relevance:** Literature sources were required to cover, at a minimum, one of the key words or search terms.
- **Region:** Priority was given to sources from Scotland, the North Sea, and the UK. Sources based in the Northeast Atlantic and Europe were given second priority followed by sources based in the North Atlantic, and the Arctic Ocean. Sources with a general global context and sources from other countries with adjacent seas were also included at the lowest priority level.
- **Species:** To answer research Q1 and Q2, studies with only the commercial species of interest were included.

An online workshop was also conducted by the project team with the aim of gaining insight to the questions posed through engaging with experts and discussing the outcome of the literature review. Input from the attendees was logged and used to inform this report.

Further details of these steps, search terms, key words and species of interest can be found in **Appendix A**: Methodological approach.

3 Key findings

3.1 Changes in distribution and productivity of key commercial fish species

Scottish waters are currently exhibiting warming trends with increases to sea surface temperature (SST) higher than the global average. Several species have exhibited changes in range and distribution over the last 30 years due to these climate change impacts. The timing of life events is also changing. It is predicted future warming could result in mismatched spawning, causing greater ranges and longer larval phases. As distributions shift, and changes to life cycles occur, food availability and species interactions are altering. These shifts have been identified as a major threat to Scottish fisheries by experts. These changes resulting in ecosystem mismatches, are leading to lower body mass of adult fish and overall declines in productivity. It is of key importance that fisheries management incorporates understanding of these issues into future strategy.

The waters surrounding the British Isles are currently seeing extreme warming with increases to sea surface temperature (SST) of over 1 °C above the global average during the last 25 years (Pinnegar *et al.*, 2017; Townhill *et al.*, 2023). Along with these changes in temperature, changes in the frequency of severe weather events, mixing of the water column, and the altering of seawater chemistry through ocean acidification and reduced oxygen levels are also impacting the marine environment (Cheung *et al*., 2012). As found throughout the literature, these recorded changes in climate are already shifting species distribution, altering major life events such as spawning and hatching and changing the productivity levels of marine organisms (Payne *et al*., 2021).

3.1.1. Plankton

In order to fully assess the impact of climate on commercial fish stocks, understanding its impacts on plankton is vital, as these micro-organisms form the base of all marine ecosystems. Changes in plankton communities affect all higher trophic levels, including shellfish, fish, and seabirds (Holland *et al*., 2023). As Scotland strives to achieve 'Good Environmental Status' plankton will play a large role as 'model organisms' in measuring environmental changes, as they are dependent on solar energy, temperature, water stratification and dissolved nutrients (Edwards *et al.*, 2020). The recent assessment of coastal and shelf pelagic habitats in the Greater North Sea as 'not good', under the current definition, and a general decrease in zooplankton and phytoplankton abundance and/or biomass over the last 60 years is cause for concern (OSPAR, 2023).

At a global and regional scale, many species of plankton have been observed to be exhibiting changes in life cycles in the northeast Atlantic due to rises in SST, altered stratification and nutrient levels (Holland *et al*., 2023). Along with these changes in life cycle and SST, altered Northeast Atlantic Oscillation (NAO) index (a physical phenomenon resulting in fluctuation of atmospheric pressure over the North Atlantic Ocean impacting weather conditions) and the increase of harmful algal blooms (HABs) have also been found to be leading factors in plankton distribution shifts (Pitois, *et al*., 2012; Bresnan *et al*., 2013). These changes in climate and life cycles have led to dominant plankton species such as the copepod crustacean *Calanus finmarchicus* declining in biomass by 70% since the 1960s and shifting northward in distribution at up to 22 km a year (Edwards *et al*., 2013; Olin *et al*., 2022). As these shifts and declines in biomass continue to occur, key fish species may also adapt by shifting distributions to match those of their prey.

3.1.2 Commercial fish

Like plankton, climate change is considered a leading cause of fish distribution shifts in Scottish waters. A study conducted by Simpson *et al*. (2013) found 72% of the most abundant fish species in UK waters exhibited climate induced shifts. Baudron *et al*. (2020) identified that 19 observed species all exhibited changes in range and distribution over a 30-year period. Globally, these shifts have been observed to be trending in a poleward direction (Engelhard *et al*., 2014; Nunez-Riboni *et al.,* 2019). Engelhard *et al*. (2014) observed that cod and haddock exhibited major shifts over the last century. Pelagic fish species are estimated to move up to 600 km and demersal fish species an average of 223 km through to 2050 (Townhill *et al*., 2023; Pinnegar *et al*., 2013). At the same time, species have also been observed moving into deeper water to adapt to impacts of climate change (Pinnegar *et al*., 2017). As species distributions shift, this brings new challenges to fisheries management as fish are subject to changes in prey availability and predator-prey interactions. The recent expansion of more hake into the North Sea increasing competition with saithe for food and resources is a prime example of the challenges such shifts can present (Cormon *et al*., 2016). These distributional shifts were identified as a major threat to the Scottish fishing industry by experts during the workshop.

Depth and habitat suitability are two notable limiting factors to species ability to shift distributions in response to climate change. Demersal fish are generally limited by the suitability of the seabed for spawning, foraging and as a nursery. This typically results in smaller distributional shifts northward than are observed in pelagic species (Simpson *et al*., 2013). While pelagic species can shift northward more easily and have been found to respond quickly to changes in temperature over much of their lifecycles, some also spawn at specific localities that promote access to suitable nursery areas for hatched larvae (Baudron *et al*., 2020). Herring are a prime example of these possible constraints as they are demersal spawners (Wright *et al*., 2020).

As life events such as spawning may be constrained by habitat suitability, they may also alter through climate induced changes (Hughes *et al*., 2014). It has been predicted that future warming could result in earlier spawning causing a greater dispersal distance (+70%) and longer larval duration (+22%), although another study has shown the opposite effect where warming delays spawning in Scottish waters for sandeel (Wright *et al*., 2017). Nevertheless, larval recruitment to nursery grounds is likely to be affected (Wright *et al*., 2020). Species such as mackerel and cod have been observed supporting this prediction as they have been found altering their spawning times and locations (Jansen *et al*., 2011; Bruge *et al*., 2016). A study conducted by McQueen and Marshall (2017) estimated cod spawning periods have shifted at a rate of 0.9 weeks per decade in the Irish Sea, and between 0.8 and 1 week per decade in the northern North Sea.

3.1.3 Productivity

Food availability can impact fish recruitment through larval mortality, as suggested by a series of studies. These cascading effects on marine food-webs can exert bottom-up effects on the ecosystem impacting low trophic levels such as copepods and forage fish to higher trophic levels including marine mammals and seabirds (Pitois, *et al*., 2012). Historically abundant species such as *C. finmarchicus* are particularly important food sources for larval fish as they are a direct line to growth and survival in the first year of life (Nunez-Riboni *et al*., 2019; Olin *et al*., 2022). Species such as *C. helgolandicus* are also currently expanding from the south, quickly becoming an important copepod prey item for higher trophic species in the North Sea (Régnier, *et al*., 2017).

As changes in plankton life events and biomass occur, trophic mismatch may occur, leading to failed fish recruitment (Edwards *et al*., 2011). Declines in European cod and ecologically important sandeel stocks are often correlated to the mismatch of plankton blooms and larval hatching (Brander *et al*., 2010; Kristiansen *et al*., 2014). Studies carried out off the east coast of Scotland have observed trophic mismatch from both the timing of copepod production and sandeel hatch dates correlated with changing rates of SST (Régnier, *et al*., 2017). A second study carried out by Régnier, *et al*., (2019) found the average difference in hatching and egg production between sandeels and copepods to be 19.8 days on average.

This gap is projected to increase as SST continues to increase. Low levels of first year herring have also been found to be correlated to this trophic mismatch (Clausen *et al*., 2017). As many marine organisms are ectothermic, temperature plays an important role in regulating physiological rates such as metabolic, growth and maturation. Changes in temperature can lead to variation in mortality distribution and phenology (Régnier, *et al*., 2019).

Food availability and body size are two of the main driving factors for fish growth (Baudron *et al*., 2011). A global decline of 14%–24% between 2000 and 2050 in adult size for most fish species due to warming oceans was predicted by Cheung *et al*. (2015). This phenomenon is known as the temperature size rule (TSR) (Ikpewe *et al*., 2021). Achieving maximum body size is essential for ecological performance (Simpson *et al*., 2011). It is unclear whether larger juvenile sizes would compensate for declines in adult sizes. These alterations in the ability to reach growth requirements are likely to have long-lasting consequences on fish population dynamics pertaining to age-size structure, egg size, reproduction, overwintering mortality rates, and ultimately, recruitment (Huang *et al*., 2021). Physiological stress leading to extra energy expenditure and growth reduction will in turn lower overall production (Prokešová *et al*., 2020). Loss of ecosystem productivity was identified as one of the greatest threats to fisheries during expert engagement.

Cumulative impacts resulting from the changing ocean climate is generally considered to be a significant threat for fisheries amongst experts. While temperature is a main factor in fish growth and recruitment, oxygen supply can also limit the maximum body size of fishes (Forster *et al*., 2012; Townhill *et al.*, 2017). The increased metabolic rate associated with higher temperatures results in an increased requirement for oxygen; the lower oxygen content of warm water adds an additional constraint (Breitburg *et al*., 2018). Physical phenomena such as the NAO has also been identified as a driver in growth rates and recruitment directly and indirectly. NAO affects many physical mechanisms, including wind speed and direction, differences in air temperature and rainfall, heat content, sea surface temperature, gyre circulation, mixed layer depth, salinity, high-latitude deep water formation, and sea ice cover. These mechanisms impacted by NAO can have adverse impacts on the abundance, recruitment, catchability, and body condition of fish stocks (Báez *et al*., 2021).

Furthermore, ocean acidification may contribute to decreased recruitment, growth, and survival of stocks; as temperatures continue to rise, some species may become more vulnerable (Cheung *et al.,* 2012; Edwards *et al*., 2020). It is important to note that while decreases in growth and productivity are recorded, trends may not be reflecting the level of resilience from species to species. A study conducted by Kaschner *et al*. (2010) looking at key commercial fish species found boreal (northern) species including cod and haddock to have a lower temperature optimum compared to the temperate species saithe and whiting. Haddock had the greatest reduction of adult body size in response to warming, however they also showed the quickest reversal of this reduction once temperatures started to decrease. This is one example of how temperature induced stress may be adapted differently from one species to another leading to different rates of long-term impacts. The observed decreases in productivity and changes in distribution will plausibly lead to future decreases in total catch value and weight (Jones *et al*., 2015; Kühn *et al*., 2023). Due to the dynamics of the current ecosystems, it is vital that more attention is given to detecting quick changes in productivity and shifts, to allow a response before these undesirable effects are irreversible (Ojea *et al*., 2021). Globally, adapted fisheries management could successfully help to control the productivity and distribution challenges of stocks under climate change pressure (Gaines *et al*., 2018).

3.2 Impacts of climate change on fisheries and industry resilience

Changes to distribution and productivity could impact fisheries through loss of abundance and decreases in landings. As fish distributions shift, access may also be limited as distances travelled from ports to fish increase and stocks cross political jurisdiction boundaries. Fishing effort may also be limited as climate continues to change weather patterns and extreme weather, such as storms, increase in frequency. The discussed impact on recruitment will affect fishing effort, leading to lower catch per unit effort (and thus a higher effort to achieve a given catch). Industry resilience could be impacted by these changes. Adaptation at an ecological and socioeconomic level is needed to help increase overall resilience.

The implications of depleting stock abundance can be detrimental to marine ecosystems and societies relying on the marine environment for food and economic stability (Simpson *et al*., 2011; Ikpewe *et al*., 2021). As key commercial fish species shift northward in distribution to more suitable water temperatures, and productivity levels fluctuate, some previously abundant stocks are decreasing in Scottish waters (Pinnegar *et al.,* 2013). These shifts in distribution and productivity must be addressed as the abundance of key commercial fish communities deplete. As stocks deplete, the resilience of fisheries is also damaged due to a reduction in genetic and generational diversity (Cheung *et al*., 2012; Ojea *et al*., 2021). Although building the resilience of fisheries in the face of the outlined challenges is difficult, there are ways to aid resilience to stocks of key commercial fish species (Ojea *et al*., 2021).

3.2.1 Impacts to fisheries

As discussed in Section 3.1, key species such as cod and mackerel are predicted to shift out of Scottish waters in large numbers as temperatures rise over the next 30 years. While there may be a decrease of landings in cold water species, these shifts also open opportunities for emerging fisheries (Cheung et al., 2012; Townhill *et al.,* 2023). Warm water species shifting north will instigate new challenges and opportunities for Scottish fisheries, as outlined in Case Study 1. As abundance of some species decrease or increase, quotas will need to be reassessed according to current availability of stocks in Scottish waters. Emerging species will be discussed in more detail through Section 3.4.

Access to resources is another factor to consider when analysing impacts on fisheries from climate induced changes. For example, experts indicate that if climate change were to increase the frequency and intensity of storms, it could result in a decrease in available fishing effort days, reducing the ability of fishing boats to access stocks (Cheung *et al*., 2012). Further losses to fisheries will be seen in the form of quality of landings as body size and productivity of major stocks decrease. As fish distributions shift, access may also be limited as distances travelled from ports increase and stocks cross political boundaries where quotas may vary (Gullestad *et al*., 2020; Maureaud *et al*., 2020; Pinsky *et al*., 2020). Experts highlight the ripple effect of the dispute on the industry considering the example of mackerel fisheries. A past dispute between Northern European countries outlined by Pinnegar *et al.* (2017) provides a model example of the challenges transboundary shifts present; an apparent shifting of mackerel from out of Norwegian waters between 2009 and 2011 resulted in disagreements over allowed catches by Norwegian vessels in EU waters as Iceland and the Faroe Islands both laid claim to increased quotas for mackerel. The mobility of fleets could be seen as a pivotal tool for long term fisheries adaptation to climate induced shifts in ecosystems. Despite this increasing adaptive capacity, there will likely be trade-offs between factors such as increasing fuel costs and greenhouse gas emissions, with a potential requirement for vessel changes. It should also be noted that distribution changes are not currently reflected in fisheries agreements for shared stocks, as experts highlighted during the engagement, stressing the importance of addressing quota distribution. These challenges may require transformational change in the management system of international agreements regarding relative stability and fishing quotas (Ojea *et al.,* 2021).

Hake is a good example of the problems that can be caused by the mismatch between fisheries allocations and current fish stock distributions. Within the CFP of the EU, fishing opportunities are allocated in such a way as to ensure the relative stability of the fishing activities of each Member State for each stock concerned. However, relative stability and total allowable catch (TAC) use a fixed allocation based largely on historical catch records for each country in 1973–1978. When these relative stability allocations were devised, hake landings in the North Sea were negligible. As a result, relative stability allocates only 3% of the TAC to the North Sea. However, the North Sea now has 34% of the entire hake stock, which led to massive discarding of hake that couldn't be returned to port. Scottish fleets landed 3,035 tonnes of hake in the North Sea. In 2011, with 2,678 tonnes of this coming from quota swaps, yet they still discarded 4,993 tonnes (Baudron *et al*., 2020). As evidence mounts for changes in the distribution of commercial fish, up-to-date data is crucial if fish stocks are to be managed sustainably. Collaborating with scientists, policymakers, and stakeholders to develop adaptive management approaches that consider the changing distribution of fish species can help optimise the exploitation of new commercial species.

Case Study 1: Emerging Scottish hake fishery impacts as an example of shifting distributions and emerging fisheries challenges and opportunities.

3.2.2 Resilience in fisheries

Climate related challenges presented to Scottish fisheries impact the level of resilience. Overall, the resilience of fisheries can be looked at through two lenses: an ecological lens, understood to entail the ability of ecosystems or species to recover after a disturbance; or a socio-economic lens, stated to include the capacity to adapt in case of stress or change along with institutional resilience, as the capacity of a natural resource governance system to absorb a disturbance while maintaining its major structures and functions (Ojea *et al*., 2021). Both sides are equally important to consider building a comprehensive understanding of the implications of climate change on Scottish fisheries.

While there are challenges with fisheries resilience such as genetics and age diversity (as discussed previously), recovery time is also a determining factor in a species' ability to incorporate a pattern of resilience (Ojea *et al*., 2021). There are many ways species can adapt to build resilience as climate changes. Resilient species can adapt to environmental fluctuations through incorporating broader environmental niches, adult range and distribution shifts, habitat diversity and dietary flexibility (Mason *et al*., 2021). Although species are characterised by the ability to adapt to changing environments to survive (natural selection) it is important to consider how quickly this evolution and adaptation may take place relative to rate of climate related changes. Failure to adapt can often result in a collapsed fishery as highlighted in Case Study 2.

From a socio-economic point of view, autonomous adaptation has played, and will continue to play a vital role in the fishing industry as highlighted during the expert engagement workshop. Nevertheless, it was pointed out that there are certain management challenges to consider as climate change may impact the resilience of fisheries in many ways. For instance, many aspects of resilient-friendly fishing practices can be damaging from an ecological perspective. An example of this is fishermen utilising a 'crop rotation' style of fishing: as fish stocks in certain areas deplete, fishermen are able to respond to the change and move to a new area until that area is depleted. While this cycle does build socio-economic resilience, it does so at the cost of ecological resilience. As this cycle repeats, areas may not recover well, setting up stocks for continued failure. Such practices eventually create a unique management challenge that will need support to incentivise fishermen to adopt more sustainable methods. Baudron *et al*. (2020) noted that beyond productivity and recruitment, fishing is one of the main factors impacting the abundance of commercial fish species. This is further supported by Brander *et al*. (2010) suggesting that reducing fishing pressure can become a strategy to reduce the impacts of climate change. In addition, an important factor impacting fisheries resilience is overexploitation (Ojea *et al*., 2016), this should be considered in strategies aiming to build further resilience through introducing new policies to ensure sustainable fishing practices are enforced and to create opportunities for fishermen to seek diversification and alternate income sources. As highlighted by experts during the workshop, controlling fishing pressure is vital as stocks can respond to factors like lower fishing mortality, that can potentially override climate effects, in turn, providing temporary relief from climate change and ensuring resilience.

Fisheries management in Alaska is considered some of the most effective in the world; nevertheless, despite this highly regarded management system collapse is still a threat. The eastern Bering Sea snow crab fishery in Alaska worth 150 million USD provides a prime example of how fast climate can destabilise a large fishery. Three years after an all-time high of abundance in 2018, the snow crab stock collapsed in 2021 with more than 10 billion crabs disappearing from the eastern Bering Sea shelf. Several observations suggested that temperature and population density were the two key variables resulting in the collapse. The collapse is recorded as one of the largest global reported losses of motile marine macro fauna resulting from marine heatwaves. The caloric requirements for snow crabs nearly double as temperatures rise from 0°C to 3°C. This, coupled with a limited foraging area, suggest that starvation likely played a role in the collapse. This example of a collapsing snow crab population suggests that considering environmental influence in estimates of biomass used to set catch limits can be important but does not resolve the standing question of how to consider environmental change in management targets. The example also highlights the importance of adaptive capacity of species as there continues to be uncertainty for future warming trends.

Case Study 2: Alaskan snow crab fishery as an example showing how climate can quickly destabilise a strong fishery if a species cannot adapt to changes in a timely manner.

3.3 Climate change impact on delivering policy outcomes

3.3.1. Reaching Maximum Sustainable Yield (MSY) within a stock

The effects of climate change on maximum sustainable yield (MSY) vary by region, depending on factors like water temperature and local hydrodynamics. Some areas may experience more negative impacts on MSY due to climate change and ocean acidification, leading to declines in fish yields during certain seasons. Fish populations may also become more vulnerable to short-term natural climate variability in the presence of other stressors such as overfishing. Climate change could increase trophic mismatch which leads to a decline in recruitment and therefore MSY. These factors highlight the complexity introduced when considering MSY in light of climate change effects which calls for a review of traditional MSY approaches.

Future biological, physiological, and geographical shifts due to climate change pose significant challenges to achieving maximum sustainable yield (MSY) within fish stocks. MSY is a theoretical concept in fisheries management, which aims to find the balance between harvesting a renewable resource and maintaining its sustainability for future generations (Rindorf *et al*., 2017). MSY represents the highest yield that can theoretically be taken from a stock in the long term without risk to stock sustainability. MSY can be determined through either surplus production models or age-structure models. The former uses catch and effort or abundance data, while the latter considers factors like growth, maturation, selectivity, mortality rates, and recruitment to determine optimal harvest levels. MSY-based fisheries management revolves around the management of fishing mortality, and hence the FMSY index (the rate of fishing mortality consistent with achieving MSY) is central.

Winter *et al*. (2020) highlights the role of the Allee effect, which describes the decline in growth rate at a small population density, in worsening the impact of human-induced stressors including fishing and climate change on fish stocks through the promotion of hysteresis (a phenomenon where the response of fish populations to environmental changes exhibits a lag or delay in its trajectory). Hysteresis can lead to a collapse in population and recovery failure, which can be irreversible. Climate change has the potential to strengthen density dependent interactions such as Allee effects, where growth rate declines at a small population density, which could increasingly challenge fisheries management (Winter *et al*., 2020).

Increases in water temperature due to climate change can affect the growth rates and maturation of juvenile fish, leading to a lower maximum size-at-age, as discussed previously (Marshall *et al*., 2019; Hunter *et al*., 2019). Baudron *et al*. (2011) discusses the implications of a warming North Sea for the growth of haddock. Baudron *et al*. (2014) shows that as temperatures increase, fish tend to have smaller body sizes, which can lead to a decrease in yield-per-recruit of these stocks by an average of 23%. Although this suggests that undertaking stock projections including environmental drivers such as temperature could affect perception of the stock status and improve the accuracy of yield forecasts, this would only be the case where projections of environmental drivers were reliable with a clear causal link between a specific driver and metrics such as fish recruitment, growth and mortality, which often is not the case. Thus, hysteresis is a reason why it may not be appropriate to build environmental variables explicitly in stock assessment models due to the use of potentially inaccurate timings of impacts.

As discussed in Section 3.1, water temperature changes can also alter fish distribution and migratory patterns, encouraging certain species to shift to cooler waters, thereby increasing the complexity of sustainable stock management (Marshall *et al*., 2019; Bahri *et al*., 2021). Spawning times are also affected by SST which in turn impacts the survival of eggs and larvae, and ultimately the size of the adult population (Bahri *et al*., 2021). Changes in climate can also affect the productivity of marine ecosystems, which can in turn affect the abundance and distribution of fish stocks (Marshall *et al*., 2019). Pinnegar *et al*. (2013) states that long-term climate change may make MSY more difficult to achieve by reducing the overall carrying capacity (the maximum population that a given ecosystem can sustainably support over the long term), which means that the stock may not be sustained at levels observed in previous years. Additionally, extensive fishing can cause fish populations to become more vulnerable to short-term natural climate variability, making them less able to buffer against the effects of poor year classes. A predictive study by Régnier *et al*. (2019) found that projected warming scenarios could increase the trophic mismatch between predator and prey, leading to a decline in recruitment (the number of young fish that enter the population each year). Further studies have found evidence that climate change can affect recruitment, which is predicted to hinder the ability of fisheries to attain MSY of the stock (Kühn *et al*., 2023).

According to a paper by Van Leeuwen *et al*. (2016), the effects of climate change and ocean acidification on MSY is dynamic and varies according to the site's hydrodynamic regime (the prevailing patterns of water movement, including currents, tides, and circulation). The paper studied three sites in the central and southern North Sea with varying hydrodynamic regimes: seasonal thermal stratification, permanently mixed, and large inter-annual variability. Based on the models, under a medium emissions climate change scenario, the site characterised by large interannual variability was predicted to decrease in yield, especially in winter. This was primarily due to the impacts of ocean acidification on the benthic system due to its role in passing carbon to higher trophic levels. The remaining two sites, one with seasonal thermal stratification and the other with permanently mixed waters, showed an increase in fisheries yield in response to the stressors. This demonstrates that sites with varying hydrodynamic regimes will show differing responses to climate change and ocean acidification and ultimately represent different trends in fisheries harvest.

All these factors can make it more difficult to sustainably harvest fish at the same level as was previously possible and therefore hinder the ability to achieve MSY within a commercial fish stock. These complexities call for proactive and adaptive management approaches to sustainably exploit fisheries resources under changing climatic conditions (Marshall *et al*., 2019; Bastardie *et al*., 2022). Regenerating degraded stocks to levels that are higher than those required to generate MSY would help populations become sufficiently large and diverse as to be more resilient to climate change (Kemp *et al*., 2023). This is because larger and more diverse populations are better able to adapt to changing environmental conditions. Therefore, it is important to manage fisheries in a way that allows fish stocks to regenerate to levels higher than those required for MSY. Similarly, Bastardie *et al*. (2022) suggests that the risk of losing an entire stock due to climate change is greater than the risk of losing a small portion of it.

As highlighted during the workshop, FMSY is often treated in policy as a simplified and specific numerical goal that assumes constant conditions, predictable fish population dynamics, and no external factors affecting the ecosystem. In reality, FMSY is a dynamic and variable metric that is regularly updated whenever there is a significant change to a stock assessment which serves to account for ongoing climate change. It may be used as a reference point to guide the allowable catch limits for a particular fishery, to prevent overfishing and promote sustainability by capping the maximum allowable catch based on the calculated MSY value. Ecosystems are dynamic, and fish populations are influenced by various factors, including climate change, habitat alteration, predation, and fishing practices. These factors can cause fluctuations in fish abundance and distribution. Therefore, the use of MSY may not be appropriate in all situations and could be adapted to the specific ecological and environmental context.

Overall, the impacts of climate change on fish populations leads to a requirement for a fundamental re-evaluation of traditional fisheries management practices. Policies that treat MSY as a static, numerical target may no longer be sufficient in the face of changing ecosystems and climates (Travers-Trolet *et al*., 2020). To adapt to these new complexities and uncertainties, a proactive and adaptive approach is essential. Reframing fisheries policy can provide resilience against the unpredictability of climate change, and as global demand for resources and food security grows, understanding and applying these principles become increasingly vital for a sustainable future.

3.3.2. Area-based management tools

Area-based management tools including areas closed to fishing (either temporarily or permanently) or MPAs can provide refuge for fish populations, protection for nursery areas, and regenerate degraded habitats. However, the efficacy of these tools as an effective conservation measure varies across species. Whilst suited to sessile species, their effectiveness as a fisheries management tool is species specific. Climate change, in time, may also alter the effectiveness of area-based management as tools due to stock distribution shifts. Hence, area-based management where the objective is to increase biodiversity may be more resilient with time.

There are a number of locations in Scottish waters where fishing closures are enacted, on particular species, or at particular times of year (eg spawning periods). Global evidence suggests that area-based management tools, such as marine protected areas (MPAs) and other examples of marine spatial planning, may have varying levels of effectiveness for highly mobile species in a world increasingly affected by climate change, with some no longer being optimally located. Grafton *et al*. (2023) states that climate change is one of the key drivers of risks for marine capture fisheries (MCFs) and poses critical risks for important natural capital stocks. The projected changes in fish distribution resulting from climate change pose complex challenges for the implementation and success of closed areas in achieving conservation objectives (Grafton *et al*., 2023). Climate change can potentially alter the effectiveness of these areas by causing shifts in the distribution of target species, which may move beyond the boundaries of the protected area (Pinnegar *et al*., 2017). This can make technical measures such as area closures less effective in protecting target species, especially for highly mobile species such as many commercial fish. Another way in which climate change affects the efficacy of area-based management tools is by interacting with non-climatic drivers, such as overfishing and the seabed abrasion associated with some fishing activity, which increases vulnerability to climate change and potentially weakens ecosystem resilience (Hoppit *et al*., 2022). Nevertheless, there is evidence that using MPAs as an approach to promote resilience, especially in key, early life stages, helps to buffer marine communities against the impacts of climate change and is of vital importance (Wilson *et al*., 2020; Grafton *et al*., 2023).

Although is rare for MPAs to be designed specifically for the conservation of commercial fish species in Scotland, the North-west Orkney Nature Conservation (NC) MPA is an example where sandeels are protected primarily due to its role as a key prey species for marine mammals and seabirds (JNCC, 2021). Despite this MPA being no longer directly relevant to the commercial fishing industry due to the recent closure of sandeel fisheries, the protection of sandeels has an indirect impact on commercial fisheries as Atlantic cod, haddock and whiting are among the species which prey upon sandeels. Regular larval surveys have been taking place within the MPA and the results indicated that persistent numbers of sandeel larvae are exported from this MPA thus replenishing surrounding populations (JNCC, 2021).

Case Study 3: Sandeels in Scottish waters and the North-west Orkney MPA

Scotland's first fully protected marine reserve was established within the Firth of Clyde in Lamlash Bay, Isle of Arran in 2008, with the goal of regenerating the local marine environment and enhancing commercial shellfish and fish populations (Howarth *et al*., 2012). In the summer of 2010, the University of York in conjunction with the Community of Arran Seabed Trust (COAST), conducted various underwater surveys in order to determine how the area was responding to its protection. They found that, since the site was designated a no-take zone (NTZ), there has been a substantial increase in biodiversity along with the size, age and density of many commercially important species (Stewart *et al.*, 2020). This case study has been used on many occasions as evidence for increasing the levels of protection in UK waters and the success of this MPA has been recognised at an international level.

Case Study 4: Scotland's first no-take zone in the Firth of Clyde in Lamlash Bay, Isle of Arran (designated in 2008)

As highlighted by these case studies, area-based management tools such as MPAs can play an indirect role in fisheries management by providing a refuge for fish and shellfish populations and their key early life-stages, by protecting and regenerating degraded critical habitats (Wilson *et al.*, 2020; Kemp *et al.*, 2023). They can also enhance the resilience of ecosystems to climate change by protecting and regenerating ecosystem complexity (Kemp *et al.*, 2023). Indirectly, MPAs can support fisheries through a phenomenon known as the spill over effect, which occurs when the impacts of these protected areas extend beyond their boundaries and into the surrounding fishing areas, although this is not the primary goal of MPAs (Stobart *et al.*, 2009). From an ecological standpoint, spill over effects result from an increase of fish biomass within the protected area due to a reduction of mortality which can subsequently 'spill over' into the surrounding area via the migration of adults, or the dispersion of eggs or larvae. These protected areas serve as reservoirs for reproduction, as the larvae and juveniles produced within them disperse to adjacent areas, replenishing populations in the surrounding fishing grounds. All these factors carry economic benefits, as evidence suggests they translate into the potential for increased catch for fishermen. Despite the increased abundance of fish due to the positive effects of area-based management and MPAs on fish stocks, it is important to note that fishermen may face limitations in terms of what and how much they can catch due to already established quotas. This highlights the necessity of adaptive and dynamic management strategies that allow for changes to be made at a fast enough rate for fishermen to reap the rewards (Pinnegar *et al.*, 2017).

Area-based management tools are generally static in nature and are rarely designed to consider ecological responses to climate change. As previously stated, climate-induced changes in ocean conditions and extreme events challenge MPA resilience, emphasising the importance of designing flexible, proactive, and climate-resilient MPAs (Hopkins *et al.*, 2016; Schmidt *et al.*, 2022). Ensuring the benefits of MPAs for fisheries, the wider ecosystem, and associated ecosystem services, while avoiding maladaptation and promoting sustainability, is essential (Brooker *et al.*, 2018). Management is typically slow to adapt to these changes by modifying long-held management rules in the face of climate change (Pinnegar *et al.*, 2017), an observation that was reflected in the engagement workshop.

While there are obvious advantages to having well informed and well managed area-based management tools implemented throughout Scottish waters, Wilson *et al.* (2020) states that there are barriers to adopting climate change adaptation strategies, such as a lack of scientific studies evaluating different adaptation strategies and shortcomings in current governance structures. Additionally, decisions about area-based management implementation have the potential to increase the tension between conservation, economic consideration, energy production, fisheries, and infrastructure (Hoppit *et al*., 2022).

This indicates that the role and impact of MPAs in supporting commercial fisheries can vary widely depending on local factors, and their effectiveness may not be universally applicable across all fisheries. Therefore, other area-based management tools should be considered in conjunction with MPAs in order to promote resilience in commercial fisheries against climate change. Although, it is acknowledged that MPAs often have alternative objectives beyond fish resilience and commercial fish stocks, for example in supporting seabird populations.

In light of these findings, adapting to changes in climate are of critical importance and there are developing areas where this can be informed through data driven modelling. The development of habitat suitability modelling techniques can help predict the potential impact of climate change on the natural distribution of species, which can inform the management of MPAs (Pinnegar *et al*., 2017). These models look at current tolerated temperatures by certain species and predict distribution shifts, if it is known how the environment may change in the future. Previous models have predicted that commercially important species over the next 50 years are likely to continue to shift, and in the north-east Atlantic specifically (Cheung *et al*., 2010; Lindegren *et al*., 2010; Cheung *et al*., 2011).

Overall, there is an intricate relationship between area-based management tools such as MPAs, climate change and the role of policy. While area-based management can offer benefits to fisheries by acting as sanctuaries for fish populations and safeguarding habitats critical for the life cycle of commercial fish, their effectiveness may be influenced by climate change-induced shifts in species distribution and other local factors such as size of the area and current management strategies. As climate change poses a significant risk to MCFs and crucial natural capital stocks, the need for adaptive and climate resilient area-based management strategies become evident. Additionally, tensions between sectors highlights the intricacy and complexity of policy and decision making that is involved. In the face of climate change, it is critical that tailored, flexible, and science-based policy frameworks are implemented to ensure the success of area-based management tools in promoting both ecological resilience and sustainable fisheries.

3.3.3. Limiting inshore activity to current levels

The intended policy to limit inshore activity to current levels will not be compromised by climate change, but may rather help to address the challenges posed by reducing the pressure on inshore fish stocks and ecosystems, while also protecting seabed habitats. Climate change is projected to have many effects on commercial fish species, including those that are currently fished inshore or utilise the inshore environment at some point in their life cycle. These effects include changes in habitat suitability, distribution, and productivity. Disruptive fishing methods, such as trawling and dredging, can damage seabed habitats important for inshore fish and shellfish. Therefore, limiting the pressure from disruptive fishing methods may increase resilience of inshore ecosystems to the impacts of climate change.

In August 2021, the Scottish Government set out its intention to consult on applying a cap to fishing activity in inshore waters that will limit activity to current levels and set a ceiling from which activities that can disrupt the seabed may be reduced as evidence becomes available. This is now part of a wider package of inshore measures which are currently being developed in collaboration with stakeholders with an immediate focus on improving inshore fisheries management, by helping to transition to more agile, localised systems of management, that make more regular use of scientific advice to balance environmental, social and economic outcomes.

The commercial shellfish species harvested in the inshore region are exposed to risks from climate change. Research conducted on the scallop fishery off the Isle of Man indicated a positive correlation between seawater temperature during spawning season and the number of young scallops produced each year. Additionally, adult scallops in warmer years had larger gonads, indicating higher egg production (Cheung *et al*., 2012). While king scallops seem to be relatively resilient to CO_2-induced ocean acidification, their allocation of resources between tissue and shell production varies seasonally in response to this stressor (Cameron *et al*., 2019). As well as this, climate change has the potential to increase likelihood of HABs, resulting in shellfish harvesting area closures (Bresnan *et al*., 2013). Therefore, although climate change may lead to an improvement in scallop recruitment around the UK, there is a risk that the productivity of the fishery may decrease, or that the fishery will have to be closed due to potential impacts on human health.

Nephrops, which are in the colder segment of their thermal range in Scotland, are anticipated to not exhibit any major changes under the temperature projections (Serpetti *et al*., 2017). Studies suggest that increased marine temperature has caused an earlier shift in their larval phenology, however so far this has had minimal effects on larval retention and advection distance overall (McGeady *et al*., 2021). Populations of *Nephrops* found off the west coast of Scotland are supplemented by larvae exported from western Irish Sea *Nephrops* populations, which may be important for recruitment when native larval retention is low (McGeady *et al*., 2021). However, habitat suitability for *Nephrops* populations along the west coast of Scotland may decrease in the future due to climate change (Townhill *et al*., 2023). Therefore, although *Nephrops* populations are exhibiting adaptability to the effects of climate change, as evidenced by the limited impact on larval retention and advection, the potential decline in habitat suitability along the west coast of Scotland raises concerns about the long-term persistence of these populations.

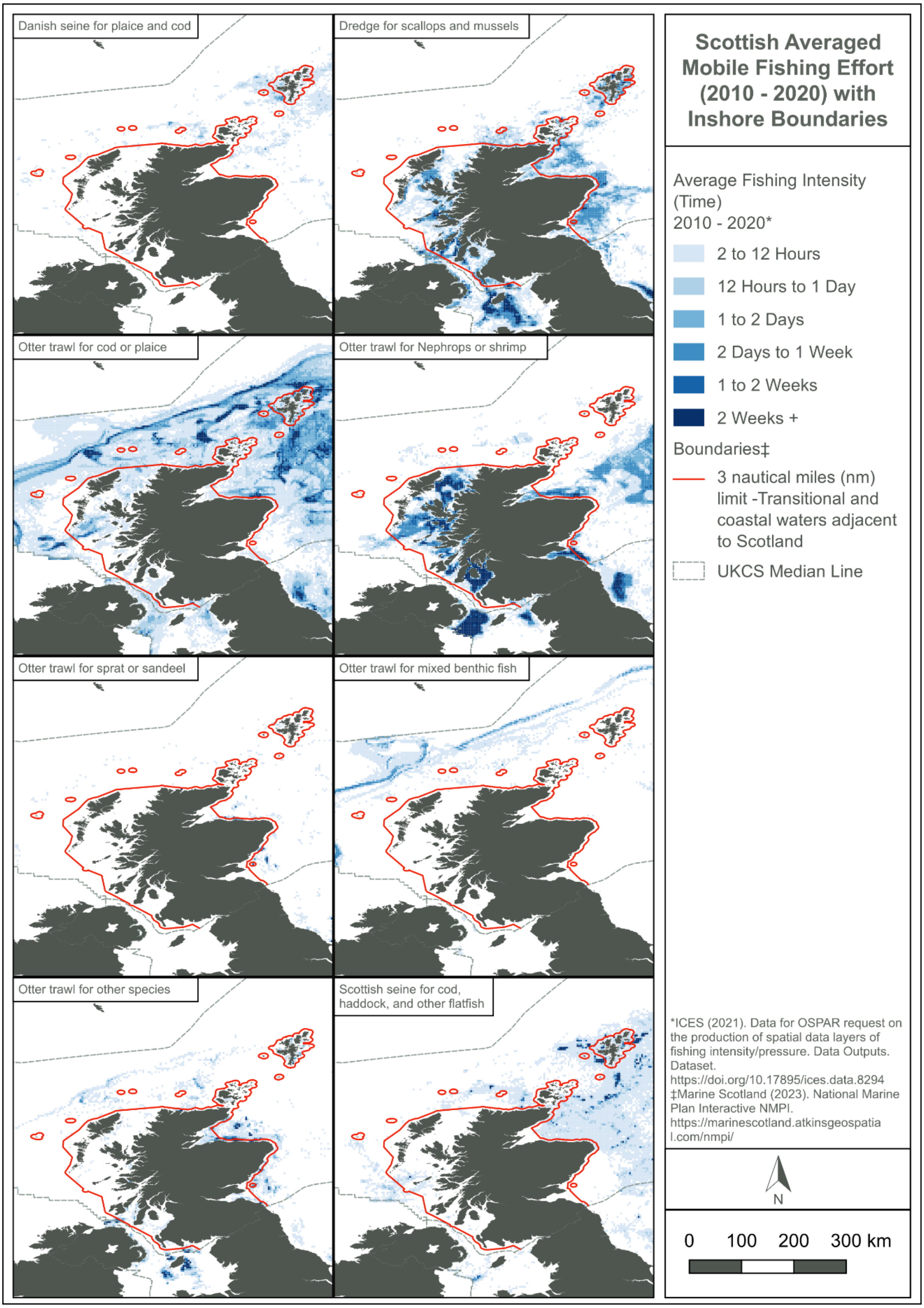
Fishing effort within the inshore region ranges from low-impact fishing methods using divers to handpick scallops, static gear such as creels and pots to target crab and lobster, to more disruptive mobile gear methods such as dredging and trawling (Davies *et al*., 2021). Within the Scottish territorial sea, otter trawls for *Nephrops* and shrimp, and dredges for scallops and mussels appear to have the highest averaged inshore fishing intensity between 2010 and 2020 (ICES, 2021; Figure 2). However, bottom trawling and dredging were identified in

Scotland's Marine Assessment as one of the most widespread and direct pressures across Scottish waters (Moffat *et al*., 2020).

Many commercial species at risk from climate change will utilise the coastal benthic environment at some point during their life cycle, likely as nursery or spawning areas (Wright *et al*., 2020). It is crucial to identify points in a species' life cycle where they are most susceptible to the impacts of climate change to minimise human pressures on struggling stocks (Wright *et al*., 2020). For example, Atlantic herring, a commercially important species which is projected to have a decrease in habitat suitability in the UK due to climate change (Townhill *et al*., 2023), has been recorded as utilising a variety of coastal benthic environments as spawning grounds around Scotland, including live maerl beds, kelp, sea firs, and broken mollusc shell beds (Frost and Diele, 2022). However, bottom trawling and dredging activities can alter the physical and biological characteristics of these benthic environments, putting them at risk (Ryan and Bailey 2012; Frost and Diele, 2022).

Disruptive fishing methods also put pressure on inshore ecosystems that are at risk from climate change. Scottish maerl beds, which play a crucial role not only in the spawning of herring but also in supporting other economically significant fish and shellfish including gadoid species and scallops, are highly susceptible to environmental changes, with estimated projections suggesting an 84% decline due to climate change scenarios (Kamenos *et al*., 2004a; Kamenos et al., 2004b; Simon-Nutbrown *et al*. 2020; Frost and Diele, 2022). As well as this, fjords and estuaries have been found to contain habitats with large organic carbon reservoirs and high organic carbon accumulation potential (Epstein and Roberts, 2023). Preserving organic carbon reservoirs has been recognised as a critical aspect of climate change mitigation. Trawling and dredging of the seabed may contribute to the disruption of benthic organic carbon reservoirs, with one study suggesting that 7.9 Mt $year^{-1}$ of carbon is disturbed by mobile bottom fishing gear within 3 nm of the UK (Epstein and Roberts, 2023). However, this disturbance of seabed organic carbon does not necessarily equate to the loss of organic carbon from the sediment as further research is still required to determine its end fate (Epstein *et al*., 2022). Therefore, maintaining coastal ecosystems through limiting disruptive fishing methods can be essential to provide a refuge for both species and ecosystems at risk of climate change, and may help to preserving stores of organic carbon.

Overall, the projected changes in climate do not compromise the delivery of the intended policy outcomes, as the intention to limit inshore fishing to current levels in light of the emerging evidence could become an important step in protecting inshore fish stocks and ecosystems from the impacts of climate change. Through preventing an increase in fishing pressure, and setting a ceiling on disruptive fishing methods, the policy will help towards a sustainable inshore fishery, while limiting impacts on essential inshore seabed habitats. This will provide refuges for both species and ecosystems that are at risk of climate change, while also building resilience to projected climate change scenarios.



Data sources: ICES, 2021; Marine Scotland, 2023

Figure 2: Scottish Inshore Fishery Effort Average (2010 – 2020)

3.4 Maximising access to new commercial species

Climate change is leading to a redistribution of fish species in the waters around Scotland, creating new opportunities for commercial fisheries whose traditional species may no longer be available. Species such as anchovy and seabass are projected to become more abundant in Scottish waters. Fishermen may be able to exploit new commercial species that become available in their waters, but they will need to adapt their operations and diversify their targets. There are also several constraints that inhibit UK suppliers from benefiting from these potential opportunities; domestic consumer preferences in the UK are generally for a limited range of species. Supermarkets can play a major role in this transition by educating consumers about new local commercial species and offering them a wider range of sustainable seafood options. Another constraint is that many of the new commercial species will need to be exported to markets where there is already an established demand. In order to capitalise on these potential emerging opportunities, Scotland needs to establish market access early for these new species.

3.4.1. New commercial species

As discussed in Sections 3.1 and 3.2, climate change is leading to distribution changes in commercial fish species in the Northeast Atlantic. While some species will experience a decrease in suitable habitat as a result of future climate change, many species may see an increase in suitable habitat (Townhill *et al*., 2023; Wright *et al*., 2020; Serpetti *et al*., 2017), and will therefore expand into areas where they can be targeted for exploitation by commercial fisheries in Scotland.

There have already been distributional shifts in species with warm water affinity in the UK, with observed increases in abundance of Lusitanian (southern) species being recorded during warmer periods, with coinciding decreases in the abundance of colder water boreal species. One of the primary reasons for this is that temperature is a constraint on marine ectothermic organisms, which affects critical biochemical and physiological rates such as oxygen demand, behaviour and development. Within the past three decades, a significant increase in the spatial occurrence of a number of fish species has been recorded. Presence-absence analysis conducted in the Northeast Atlantic found that of the 35 fish species observed with typically southerly distributions, 94% showed significant increases in spatial occurrence in the seven northernmost International Council for the Exploration of the Sea (ICES) divisions, including anchovy, horse mackerel, anglerfish, hake, megrim, blue whiting, mackerel, pollack, saithe and Norway pout. These increases were particularly pronounced for the two southernmost species, horse mackerel and anchovy, which were observed in six of the seven northernmost ICES divisions (Baudron *et al*., 2020). This increase in some Lusitanian species may be due to the growth of existing local populations. For instance, warmer temperatures may have allowed more anchovies to survive the winter, leading to an expansion of their range and an increase in their abundance in the southern and central North Sea (Wright et al., 2020). The occurrence of species with typically southerly distributions into new locations is positively correlated with sea-surface temperature (Montero-Serra *et al*., 2015). Seabass populations expanded into the UK in the 1990s and early 2000s during periods where there were warmer temperatures, however this expansion was halted due to over-fishing and two consecutively cold winters in 2009/10 and 2010/11 (Wright *et al*., 2020). However, sea surface temperature may be just one of several contributory factors. For example, mackerel distribution is also influenced by density-dependent factors, as mackerel have been recorded using areas of lesser habitat suitability in years when the stock size was large, suggesting that mackerel may also expand into new areas in response to competition for resources (Brunel *et al*., 2018).

Ecological models can give us a good indication of what is likely to happen under different emissions scenarios, giving an insight into possible futures for the marine environment. This information can be useful to inform decision-making and to develop strategies to mitigate future risks and maximise opportunities. However, it is important to remember that these models are a predictive tool to examine possible futures. Obtaining current, up-to-date data, is essential for understanding how ecosystems are responding to change, and for validating these predictions. Townhill *et al*. (2023) modelled the future suitability of habitat for 49 fish and shellfish species that are commercially important for the period 2030 to 2050 and 2050 to 2070, based on data from 1997-2016, in the waters surrounding the United Kingdom. The study used an ensemble of five ecological niche models, using climate projections based on three different future carbon emissions trajectories from two sources: the A1B (medium) emissions scenario from the Coupled Model Intercomparison Project (CMIP) 3 Special Report Emissions Scenarios (SRES) dataset, and the CMIP5 Representative Concentration Pathway (RCP) 4.5 (medium emissions, high mitigation) and 8.5 (high emissions, low mitigation) projections. The findings of this research indicate that waters around Scotland may become more suitable for commercial species, including but not limited to; blue whiting, brill, anchovy, hake, seabass, sprat, John dory, pollack, poor cod, pouting, red gurnard, sole, surmullet, tub gurnard, turbot, and witch (Townhill *et al*., 2023). More information, and model outputs for this study based around Scotland, can be viewed in **Appendix B**. Another modelling study, by Fernandes *et al*. (2016), who utilised the RCP 2.6 (low emissions) and an RCP 8.5 scenarios in their study, found that Scotland showed an increase in the potential catch of pelagic species under both low emissions and higher emissions scenarios up to 2050, but this effect was reversed thereafter for the high emissions scenario. Species that are eurythermal (thermally tolerant), or those belonging to the colder segment of their thermal range, such as mackerel, horse mackerel and *Nephrops*, will not exhibit any changes under the temperature projections (Serpetti *et al*., 2017). One such thermally tolerant species, whiting, is predicted to increase strongly under rising temperature scenarios, as it has a higher optimum temperature than other species, while certain predators, such as cod and grey seals, are predicted to decline (Serpetti *et al*., 2017). These projected distribution shifts may provide access to new commercial species for exploitation by fishermen whose traditional catch is no longer as plentiful. This has already been seen to an extent in the development of summer squid fisheries in the Moray Firth due to increased squid abundance (van der Kooij *et al*., 2016). Monitoring and tracking the distribution shifts of fish species can provide valuable information for fisheries management and help identify areas where new commercial species may become available (Serpetti *et al*., 2017).

3.4.2. Maximising access to new commercial species

Climate change is causing fish populations to migrate to new areas, potentially creating opportunities for harvesting new commercial species in the waters surrounding Scotland. However, several factors can hinder access to these new resources.

Quota systems can act as an obstacle to maximising access to new commercial species due to the inflexibility of quota systems that are based on historical data and agreements between nations. For example, under the EU's Common Fisheries Policy (CFP), TAC quotas are set annually based upon advice from ICES and political negotiations among member states, with the aim of maintaining relative stability of fishing activity for each country and fish stock. Since the departure of the UK from the EU and therefore the CFP, the basis of setting quotas is still based on stock advice provided by ICES, with the process of agreeing and sharing quotas requiring negotiation and arrangements between the UK and its neighbours. However, the relative stability fixed allocation keys, which vary depending on the species stock, have remained unchanged for many species since 1983, raising concerns about their representativeness and effectiveness in a changing environment (Harte *et al*., 2019). Therefore, as evidence mounts for changes in the distribution of commercial fish, up-to-date data is crucial if fish stocks are to be managed sustainably. Collaboration between fisheries scientists, policymakers, and stakeholders to develop adaptive management approaches that consider the changing distribution of fish species can promote both access to new resources and the long-term sustainability of these fisheries (Serpetti *et al*., 2017; Baudron *et al*., 2020).

Another constraint is the domestic consumer preference for a limited range of traditional species (Pinnegar *et al*., 2013). Large quantities of the fish traditionally consumed in the UK, such as cod, is derived from imports from countries further north, such as Iceland and Norway, whilst the majority of fish caught in the UK, including *Nephrops* and mackerel, is exported to southern European countries such as Spain and Portugal (Pinnegar *et al*., 2017). This feature of the UK fisheries market was also emphasised at the expert workshop. In 2021, Scottish fisheries landed 185,140 tonnes of mackerel with a value of £210 million, and 22,505 tonnes of *Nephrops* with a value of £70 million (Scottish Government, 2022). Total UK exports of mackerel for the same year was 55,922 tonnes with a value of £96 million, primarily exported to The Netherlands and other EU countries, but also China (SeaFish, 2023). For *Nephrops*, 24,141 tonnes were exported with a value of £111 million in 2021, primarily exported to France and Spain (SeaFish, 2023). Supermarkets provide around 88% of fish products in the UK by volume and value, and their influence is potentially enough to orchestrate mass scale change in the habits of the public. Pinnegar *et al*. (2017) reported that Sainsbury's 2011 "switch the fish" campaign to challenge customers to try an alternative finfish species, including some of those that are more reflective of current climatic conditions in waters around the UK and Ireland, resulted in a significant increase in seabass sales of 57% and pollack sales of 15%. These campaigns may need to be expanded to provide sustainable seafood and avoid climatic maladaptation.

New commercial species that may become available due to climate change may need to be exported to markets where there is already an established demand. These include markets for anchovy, brill, John dory, pouting, seabass, sole, sprat, and turbot, all of which had less than 200 tonnes landed in Scotland in 2021 with a value of less than £1 million. By comparison, in 2021, Scotland's total anchovy landings were around 1 tonne, whereas the Spanish fishery landed 49,582 tonnes, valued at over €84 million (EUMOFA, 2023; Scottish Government, 2022). Similarly, 30 tonnes of seabass were caught in Scottish waters in 2021, worth approximately £246,000, while French fisheries caught 2,516 tonnes, valued at €36.5 million (EUMOFA, 2023; Scottish Government, 2022). For Scotland to capitalise on these potential emerging opportunities, market access should be established early, as many of the species projected to increase their distribution in Scotland are commercially valuable within foreign markets.

3.5 Summary of key findings

The review of literature presented above illustrates a dynamic and uncertain future for the Scottish marine ecosystem and the fisheries it sustains, under the influence of a changing climate. Nevertheless, some key messages are apparent and recurring.

- There are expected to be ecosystem-level impacts due to climate change, which will likely result in distribution and ecological changes to key commercial species in Scottish waters;
- As the distributions of commercial species shift geographically, fishing grounds increase or decrease in importance and weather becomes less predictable, impact on the Scottish fishing industry is inevitable;
- Climate changes stresses could result in impacts on the value and utility of traditional MSY assessments, and a review of these may be required;
- Climate change, in time, may alter the effectiveness of area-based management tools due to fish species motility and therefore, protected sites where the objective is to increase biodiversity may be more resilient with time;
- Limiting the pressure from disruptive fishing methods may increase resilience of inshore ecosystems to the impacts of climate change;
- Redistribution of commercial species around Scotland may lead to new opportunities for the industry, but the supporting network of the industry (consumers, supermarkets etc.) needs to work in step to support diversification.

These findings point to a series of fisheries management challenges:

- The monitoring of productivity and distribution of commercially and ecologically important species;
- Transformational changes in management systems of international and local agreements regarding food stability, the introduction of new commercial species, and fishing quotas;
- The review of traditional MSY approaches, to ensure MSY and carrying capacity targets are met in the face of climate challenges;

- The use of area-based management tools to help buffer marine communities against climate change through increasing biodiversity;
- The management of fishing pressure to be adaptive and flexible going forward as fish populations may become more vulnerable in the presence of stressors such as overfishing or less resilient fishing practices;
- Changes in the habits of consumers, through supermarket campaigns, may also be needed to promote sustainable local seafood and avoid climatic maladaptation as well.

These key finding and challenges inform the following section discussing options for adaptation and development of future policy.

4 Current policy

4.1 Current strategies

Current strategies for fisheries management in Scotland incorporate scientific advice from organisations such as ICES on the status of fish stocks in the North Atlantic and the sustainable use of marine resources. Scotland, like other European countries, relies on ICES assessments to inform fisheries management decisions and many commercial stocks are jointly managed with other Coastal States.

The Marine Directorate is responsible for the management of fishing vessels in Scotland through implementing rules and policies in relation to sustainable harvest and protecting the marine environment. At a UK level, the Marine Directorate works with a number of other organisations and governmental departments including the Department for Environment Food and Rural Affairs (Defra), the Marine Management Organisation (MMO) and Seafish. Marine Directorate uses ICES advice in order to inform quotas and implement fishing limits.

Scotland's Fisheries Management Strategy 2020-2030, also known as the Future Fisheries Management (FFM) Strategy, is a strategy implemented by the Scottish Government which outlines the approach to managing Scottish fisheries from 2020 to 2030 as part of the Blue Economy Action Plan. The FFM Strategy sits broadly within Scotland's National Marine Plan (NMP) framework. It encompasses issues such as ecosystem-based management, spatial management and MPAs, recycling of gear, climate change mitigation and adaptation plans, and stakeholder collaboration and community involvement. The FFM Strategy complements the objectives set out in the UK Fisheries Act (2020) and subsequently the input into the Joint Fisheries Statement (JFS).

There are systems in place for co-management within the Marine Directorate where groups such as the Fisheries Management and Conservation Group (FMAC) and the Regional Inshore Fisheries Groups (RIFGs) are consulted both formally and informally to gain insight into the issues that stakeholders face and encourage buy in.

The Scottish National Adaptation Plan (SNAP), formerly Scottish Climate Change Adaptation Programme (SCCAP), is a five-year programme that aims to help prepare and adapt Scotland for climate change. Public consultation on the SNAP for 2024 – 2029 has recently been opened by the Scottish Government (Scottish Government, 2024). With a focus on five outcomes (i) Nature Connects; ii) Communities; iii) Public Services and Infrastructure; iv) Economy, Industry and Business; v) International Action), it is hoped that this programme will help fulfil the aims in relation to Scottish fisheries.

4.2 Challenges and barriers

Future policies may require increased focus on adaptability and flexibility in order to achieve successful management of Scottish fisheries.

As fish stocks shift distributions, it is possible that shifts across international boundaries can occur as previously discussed. Effective management requires collaboration and coordination with neighbouring countries. International agreements and cooperation may be challenged by varying interests and priorities. Another challenge is the introduction of new species moving into Scottish waters that may not have established markets causing issues with domestic consumer preferences. This may increase the need to export which does not align with Scotland's goals in relation to emissions and is less sustainable. Due to the growing variability of weather patterns as a result of climate change, there is also potential for challenges to arise in ability of fishermen to access fish stocks and meet effort-day targets.

Some species at the margin of their distribution are more vulnerable to exploitation (Rindorf *et al*., 2020). As such, knowledge of fish distribution is key to understand and manage these resources. Knowledge gaps surrounding this area of research is also a barrier. Due to changes in distribution, established MPAs for specific species may also be less beneficial to the target species in light of climate change.

This review has highlighted the importance of adaptability and flexibility in the fisheries management system.

5 Recommendations and conclusions

5.1 Recommendations for policy development, implementation, and monitoring

Following from the key findings of the literature review, here we recommend ideas for policy development, including methods for implementation and monitoring that will allow commercial fisheries management to become more adaptable in an uncertain future and address potential challenges the fishing industry might face. These recommendations and actions aim to enable effective, resilient and adaptable management by encouraging a balanced, realistic approach that reflects actual environmental changes rather than worst case scenarios or global fisheries predictions.

5.1.1. Baseline monitoring programmes

The types of habitats and related fisheries need to be further understood for specific fisheries and sectors within Scotland to enable better understanding of the capacity for adaptation and how best to support the industry in future. Therefore, research needs to be prioritised to fill significant evidence gaps or reduce uncertainty in the current level of understanding to assess the need for additional action. Further discussion of data gaps and suggested future research can be found in Section 5.2.

5.1.2. Risk / vulnerability assessments

As part of policy implementation and monitoring, climate risk assessments enable preparation and prioritisation. At a national level, a climate vulnerability assessment of Scotland's marine environment and economy (Winne *et al.* 2022), identified and evaluated methodologies and suggested how to strengthen and enhance vulnerability assessments. Risk or vulnerability assessments conducted at a local level could identify the most significant threats to individual fisheries under various future climate change scenarios, which would enable local fisheries to identify their level of exposure and vulnerability to climate change to prioritise adaptive capacity at both ecological and socio-economic levels. The assessment outputs would result in comparative and risk-equivalent advice (eg prioritising restoration of key habitats such as nursery or spawning habitats for commercial fish species).

5.1.3. Trigger points

The outputs of modelling, alongside outputs from risk assessments, may be used to inform a trigger-based approach system for fast implementation of actions and to tackle the issues around food availability and security. Triggers may be based around 'tipping points' identified by risk assessments and reaching such a trigger would activate a pre-determined sequence of actions.

Using indicative metrics (ie thresholds or targets) such as physical parameters eg temperature, monitoring data (eg egg counts) or catch metrics (MSY or bycatch levels) could be used to enable fishing fleets to adapt to maximise the potential access to new commercial species without over or under compensating. Similarly bycatch levels could be used to understand distribution shifts of new species. A multitude of metrics could be used to set triggers on a local scale, either as a single trigger point, a 'limit' of acceptable change or several triggers as part of a fishery's adaptive pathway (eg a trigger 'to plan' and potentially another trigger 'to act' to base an intervention response on) as part of its strategy. A trigger-based system is already adopted by ICES using reference points such as MSY Btrigger, a pre-determined trigger level for spawning stock biomass, as a metric.

Set triggers would force the review of data to ensure robust informative action, which would also increase flexibility and adaptability. It would require that a level of planning and research has been implemented, which would allow management decisions to be based on sound knowledge and understanding, rather than on transient global or political pressures.

5.1.4. Dynamic MSY reference points

Striving to regenerate stocks will strengthen the resilience of the stock to short-term stresses, promote genetic diversity within populations, and allow for a buffer in a changing climate. Pretty Good Yield (PGY) has been proposed in the past to account for uncertainty of estimation and implementation of MSY. The aim is to manage fishing mortality within certain boundaries of FMSY. MSY is modelled using population parameters such as mortality rates and recruitment and does not directly consider environmental variables. Instead, any significant change to a stock assessment also leads to a revision in FMSY, and Scottish Government scientists suggest that these regular revisions serve to account for ongoing climate change. A better understanding of climate change processes may allow for climatic and other environmental variables to be explicitly factored into MSY calculations and stock assessments. This will likely further increase fisheries resilience through improving the ability to forecast and provide more accurate reference points to inform quotas. Due to the unpredictability and rate of climate change, the use of historical trends may not be sufficient going forward.

5.1.5. Collaboration with stakeholders and co-management

Co-management is an increasingly important asset to help reduce barriers to management that are generally perceived as top-down. Using this more inclusive method of management, taking into account the perspectives of different stakeholders and ensuring their needs are represented will encourage buy in to new policies and success of initiatives. Co-management strategies are already in place, as discussed in Section 4.1, with the FFM Strategy having a strong focus on co-management at both local and national levels. Continuing to build on these relationships, strengthen the framework and increase trust will support the recommended policy changes. However, it will be important to consolidate the definition of co-management incorporating what it means for all stakeholders to ensure policy, industry and science are using the same definition and are working towards the same goals. Utilising the skills and practical knowledge of fishermen and incorporating that into policy is a key factor in moving forward with fisheries management in general, but also in the context of climate change. Another strategy to aid policy implementation and monitoring involves emphasis on international collaboration. Exploring partnerships with neighbouring countries and international organisations will be vital to help address shared challenges.

Aligning and coordinating fisheries policy with other policies that may impact fisheries management directly or indirectly (eg MPA management) is of vital importance to track the dissemination of knowledge and informed actions and decisions. Relationships alongside international foundations will also help to manage shared seas and fish stocks in partnership.

The policy suggestions above would result in various tools which could be used by the industry and communicated with marine stakeholders. The tools would require information to be fed from these stakeholders into those systems (eg fishermen observing changes in species or size and alerting fisheries policy) to be effective, creating a virtuous circle between stakeholders, policymakers and the industry. Supermarkets are just one of these stakeholders, who play a major role in increasing demand for new commercial species by educating consumers about new commercial species and supplying new domestic consumer preferences to the market.

5.1.6. Sustainable fishing practices

There are many methods that can be adopted to help aid the sustainability of fishing practices in Scotland. As fish stock distributions shift, the distance travelled from ports may increase, potentially resulting in increased fuel use and increased emissions. Continually exploring and implementing environmentally conscious fishing practices such as the use of fishing gear with lower environmental impact (ie reduced seabed impact, or reduced bycatch) could result in a more resilient ecosystem which should help support fishing activities through higher ecosystem biomass. Utilising seasonal closures where appropriate (for example, in specific areas during critical spawning periods), along with measures in and around known nursery areas can allow fish populations to reproduce without disturbance, building the resilience of the stock for mutual environmental and industry benefit.

5.2 Research requirements

5.2.1. Key gaps

As climate change in Scottish waters progresses, it is important that future policies account for a complete picture of the marine ecosystem to ensure effective fisheries management measures are put in place that are resilient, flexible and adaptive. Ecologically, changes to plankton and fish distribution shifts may need to be evaluated on a larger scale to inform fishing quotas and management strategies accordingly. Monitoring and tracking the distribution shifts of fish species will also be important for future fisheries management as well as a basic knowledge of the distribution of commercial and non-commercial fish species and areas important to specific life-stages (eg spawning and nursery areas).

In order to improve understanding of the impacts discussed in Section 3, additional information is required to develop knowledge gaps in several areas. Filling these gaps will allow policymakers to continue to make informed decisions to help develop the best possible solutions. Knowledge gaps at the species level could be prioritised to better understand the links between climate warming, plankton, fisheries and top predators (eg marine mammals and seabirds) in more detail to allow for more accurate predictions of future ecosystems (Edwards *et al*., 2011). Filling these gaps will allow ecosystem-based management decisions to build overall strength in the ecosystem in turn strengthening stock resilience. Other areas to explore may include studying trade-offs between temperature induced changes in body size of individuals occurring at different life stages (Ikpewe *et al*., 2021), or identifying points in a species' life cycle where they are most susceptible to the impacts of climate change to minimise human pressures on struggling stocks. Both are vital pieces of information that could help increase productivity and recruitment in stocks.

To further strengthen the adaptive capacity of Scottish fisheries, understanding the rates of genetic adaptation of individual species could be developed to aid in identifying possible future trends. Currently, there is not sufficient research into the variability in projected maximum catch potential and changes in MSY across different regions and scenarios of climate change (Travers-Trolet *et al*., 2020). Further gaps in knowledge include understanding specific mechanisms through which climate change might affect MSY, such as changes in fishing mortality rates and ecosystem dynamics; effectiveness of different management strategies in mitigating the negative effects of climate change on MSY; effects of climate change on pelagic nutrient supply, such as nitrification rates, and how these impacts translate to changes in fish biomass and fisheries yield (van Leeuwen *et al*., 2016), and finally; impacts of stresses induced by climate change on stock trajectory (Bastardie *et al*., 2022). There is a growing need for monitoring programs and pilot studies to support policymakers with scientific evidence regarding the effects of different warming scenarios on MSY, and to align research needs with policy ambition.

The effectiveness of applying caps to limit inshore fishing should be discussed further to make the most informed decisions. Along with discussing cap limits, the specific impacts of climate change on area-based management are not well understood and require further investigation. Potential interactions between climate change and other stressors, such as pollution or overfishing, which can cause compounding effects on MPAs and the species/ecosystems they are supposed to protect, are not yet fully understood or quantified. There is also uncertainty around the ability of MPAs to protect and restore ecosystems (and in turn, supporting fish stocks) under changing climate conditions due to distribution shifts of stocks, with previously established species vacating designated areas, and new species possibly favouring alternative locations. As with the example of the North-west Orkney NCMPA for the conservation of sandeel, removing a cause of mortality (ie fishing) from an area where climate change effects are identified as high, can allow some buffering effects and improve resilience to climate change. This highlights the requirement for the development of adaptive management strategies in this area. Identifying the range of different policy levers already available to deal with the issues climate change presents would be beneficial. As an example, quota swapping at both the national and sub-national level is a method used already to deal with shifting stocks. Making use of lessons learned from other countries and utilising best practices will be important.

5.2.2. Data and modelling

Enhanced research and monitoring data could result in better understanding of the capacity for Scottish fisheries to adapt. For example, more data at the local scale would help develop understanding of the effects on MSY to inform quotas relevant to the area and differentiate local trends from national or global trends. These could be incorporated as part of the Joint Fisheries Statement Fisheries Management Plans (FMPs). Any monitoring programs will need to be done in accordance with FFM Strategy regulatory and monitoring framework.

It is important to use recent data and model future changes in fish distribution and/or size to give true representation of what is a priority and realistic view of current stocks. The types of modelling recommended include investigating the effects of various climate change scenarios and habitat suitability modelling as described in Section 3.3.2. ICES is developing whole-ecosystem modelling and forecasting methodology to provide advice on climate change impacts (ICES, 2023). Data collected can be fed into these models and projections will be used to inform things such as local trigger points, MSY, TAC and stock assessments. At this stage the focus should be on preparation and gathering of data that can be fed into the models, in preparation for when the capability becomes available in the future. This further research and data collection would also be valuable to inform climate risk assessments for important commercial species so knowledge can be disseminated within the Marine Directorate and to fishermen more easily. Increasing and improving the data base will inform a range of tools and management strategies to address the threat of climate change; one of which would be the use of risk assessments.

Increased research in local regions could result in a stronger evidence base to inform ecological models. The outputs from these models under different climate scenarios may result in more accurate local future projections which could be used to develop actions to inform policy and feed into risk assessments. Examples of these informative actions could include data-driven harvest strategies for species for which new target markets are emerging and the inclusion of environmental variables in stock projections, if further research suggests this will lead to improvements.

Gaps pertaining to modelling and data also need to be met in order to form a complete picture for fisheries policy and adaptation. Models currently do not factor in all possible scenarios, such as changes in the planktonic food web or interactions between increasing temperature and ocean acidification. Incorporation of more data could increase the robustness of models and reduce uncertainty of outputs. For example, the use of a multi-decadal data set with multiple sources for plankton distribution and phenology would be useful in informing distribution shifts and monitoring productivity of the ecosystem as a whole (Holland *et al.*, 2023).

5.2.3. Future research

Here we suggest potential future research topics which may help to fill the gaps identified through this literature review and enhance wider understanding of the key driving factors behind the expected changes in fish stocks and the fishing industry.

Species distribution and ecology

A key research area is to refine knowledge of current distributions of both commercial and non-commercial fish species as well as areas relevant to key parts of their life cycle (eg spawning and nursery areas) to identify where management measures are necessary and determine margins. Additionally, studying distribution shifts to identify areas where new commercial species may become available will be beneficial. Further to this, research into biodiversity implications of climate induced shifts, including, for example, the northward shift of the copepod crustacean *C. finmarchicus*.

Lifecycle and physiological changes of species (eg early spawning effects and dietary changes with temperature, as seen in the Alaskan Snow Crab in Case Study 2) as well as food chain linkages and multispecies interactions within area closures and MPAs (eg plankton shifts). Finally, research into habitat suitability for *Nephrops* on the west coast of Scotland would be greatly beneficial given its importance for the region.

Fishing industry

Comparing projected species moving into UK waters against the potential market in the UK, could indicate levels of risk and highlight where markets may need to be further developed. In this case, using a combination of predictive data such as habitat suitability models and evidence of abundances from ICES should provide more robust estimates. Using habitat suitability models alone are unlikely to be robust enough. For example, habitat suitability for haddock was expected to decrease around Scotland from some studies (eg Townhill *et al*., 2023), but according to ICES abundance estimates, haddock has increased dramatically in recent years. This is also the case for cod and whiting, which raises the need for caution when utilising the predictive power of ecosystem-based fisheries models.

Another potential study stemming from this review could be to investigate the extent to which fishermen have had to alter their fishing practices in recent years as a direct or indirect result of climate change effects. Factors that may be affected could include whether they have had to change or diversify where they fish, invest in different gear types, or whether they have noticed new species in bycatch. A study of this nature would be valuable and would be in line with the increasing desire for co-management among policymakers, industry, and scientists. Obtaining this direct input from the industry is key for informing policy.

Another research area directly relevant to the fishing industry would be to continue to research and implement the use of more environmentally friendly gear types and the corresponding potential benefits on the marine environment, including reduced catch of non-target species and age-groups and reduced seabed disturbance. And finally, we recommend further research into how climate induced shifts in fish stocks away from ports will affect the distances travelled by fishing vessels and therefore fuel use and resulting emissions.

Ultimately, the greater the knowledge base and understanding of our marine environment, the more informed decision making and planning can be, leading to more effective fisheries management. While this report suggests potential areas for focus, marine and fisheries scientists will be best placed to drive future research efforts for maximum environmental and industry benefit.

6 References

Báez, J.C., Gimeno, L. and Real, R., 2021. North Atlantic Oscillation and fisheries management during global climate change. *Reviews in Fish Biology and Fisheries*, 31, p.319-336.

Bahri, T., Vasconcellos, M., Welch, D.J., Johnson, J., Perry, R.I., Ma, X. and Sharma, R. eds., 2021. Adaptive management of fisheries in response to climate change: FAO fisheries and aquaculture technical paper No. 667 (Vol. 667). Food & Agriculture Org.

Bastardie, F., Feary, D.A., Brunel, T., Kell, L.T., Döring, R., Metz, S., Eigaard, O.R., Basurko, O.C., Bartolino, V., Bentley, J. and Berges, B., 2022. Ten lessons on the resilience of the EU common fisheries policy towards climate change and fuel efficiency-A call for adaptive, flexible and well-informed fisheries management. *Frontiers in Marine Science*, 9, p.947150.

Baudron, A. R., Needle, C. L., and Marshall, C. T. 2011. Implications of a warming North Sea for the growth of haddock Melanogrammus aeglefinus. *Journal of Fish Biology*, 78(7), p.1874-1889.

Baudron, A.R., Brunel, T., Blanchet, M.A., Hidalgo, M., Chust, G., Brown, E.J., Kleisner, K.M., Millar, C., MacKenzie, B.R., Nikolioudakis, N. and Fernandes, J.A., 2020. Changing fish distributions challenge the effective management of European fisheries. *Ecography*, 43(4), p.494-505.

Baudron, A.R., Needle, C.L., Rijnsdorp, A.D. and Marshall, C., 2014. Warming temperatures and smaller body sizes: synchronous changes in growth of North Sea fishes. *Global Change Biology*, 20(4), pp.1023-1031.

Brander, K.M., 2010. Cod *Gadus morhua* and climate change: processes, productivity and prediction. *Journal of Fish Biology*, 77(8), p.1899-1911.

Breitburg, D., Levin, L.A., Oschlies, A., Grégoire, M., Chavez, F.P., Conley, D.J., Garçon, V., Gilbert, D., Gutiérrez, D., Isensee, K. and Jacinto, G.S., 2018. Declining oxygen in the global ocean and coastal waters. *Science*, 359(6371), p.eaam7240.

Bresnan, E., Davidson, K., Edwards, M., Fernand, L., Gowen, R., Hall, A., Kennington, K., McKinney, A., Milligan, S., Raine, R. and Silke, J., 2013. Impacts of climate change on harmful algal blooms. MCCIP Science Review 2013: 236-243

Brooker, E., Devenport, E., Hopkins, C.R., Hennige, S., Roberts, J.M. and Duncan, C., 2018. Scotland as a case study for how benefits of marine ecosystem services may contribute to the commercial fishing industry. *Marine Policy*, 93, pp.271-283.

Bruge, A., Alvarez, P., Fontán, A., Cotano, U., and Chust, G. 2016. Thermal niche tracking and future distribution of Atlantic mackerel spawning in response to ocean warming. *Frontiers in Marine Science*, 3, p.1-13.

Brunel, T., van Damme, C.J., Samson, M. and Dickey-Collas, M. 2018. Quantifying the influence of geography and environment on the northeast Atlantic mackerel spawning distribution. *Fisheries Oceanography*, 27. P.159–173.

Buxton, C.D., Hartmann, K., Kearney, R. and Gardner, C., 2014. When is spillover from marine reserves likely to benefit fisheries?. *PloS One*, 9(9), p.e107032.

Cameron, L.P., Reymond, C.E., Müller-Lundin, F., Westfield, I., Grabowski, J.H., Westphal, H. and Ries, J.B., 2019. Effects of temperature and ocean acidification on the extrapallial fluid pH, calcification rate, and condition factor of the king scallop *Pecten maximus*. *Journal of Shellfish Research*, 38(3), pp.763-777.

Cheung, W.W., Frölicher, T.L., Lam, V.W., Oyinlola, M.A., Reygondeau, G., Sumaila, U.R., Tai, T.C., the, L.C. and Wabnitz, C.C., 2021. Marine high temperature extremes amplify the impacts of climate change on fish and fisheries. *Science Advances*, 7(40), p.eabh0895.

Cheung, W.W., Pinnegar, J., Merino, G., Jones, M.C. and Barange, M., 2012. Review of climate change impacts on marine fisheries in the UK and Ireland. *Aquatic Conservation: Marine and Freshwater Ecosystems*, 22(3), pp.368-388

Cheung, W.W., Dunne, J., Sarmiento, J.L. and 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), pp.1008-1018.

Cheung, W.W., Brodeur, R.D., Okey, T.A. and Pauly, D., 2015. Projecting future changes in distributions of pelagic fish species of Northeast Pacific shelf seas. *Progress in Oceanography*, 130, pp.19-31.

Cheung, W.W., Lam, V.W., Sarmiento, J.L., Kearney, K., Watson, R.E.G., Zeller, D. and Pauly, D., 2010. Large-scale redistribution of maximum fisheries catch potential in the global ocean under climate change. *Global Change Biology*, 16(1), pp.24-35.

Clausen, L.W., Rindorf, A., van Deurs, M., Dickey-Collas, M. and Hintzen, N.T., 2017. Shifts in North Sea forage fish productivity and potential fisheries yield. *Journal of Applied Ecology*, 55(3), p.1092-1101.

Colléter, M., Gascuel, D., Albouy, C., Francour, P., de Morais, L.T., Valls, A. and Le Loc'h, F., 2014. Fishing inside or outside? A case studies analysis of potential spillover effect from marine protected areas, using food web models. *Journal of Marine Systems*, 139, pp.383-395.

Cormon, X., Kempf, A., Vermand, Y., Vinther, M. and Marchal, P., 2016. Emergence of a new predator in the North Sea. 2016. *ICES Journal of Marine Science*, 73(5), P. 1370–138. https://doi.org/10.1093/icesjms/fsw050

Davies, B.F., Holmes, L., Rees, A., Attrill, M.J., Cartwright, A.Y. and Sheehan, E.V., 2021. Ecosystem Approach to Fisheries Management works—How switching from mobile to static fishing gear improves populations of fished and non-fished species inside a marine-protected area. *Journal of Applied Ecology*, *58*(11), pp.2463-2478.

Edwards, M., Atkinson, A., Bresnan, E., Helaouet, P., McQuatters-Gollop, A., Ostle, C., Pitois, S. and Widdicombe, C., 2020. Plankton, jellyfish and climate in the North-East Atlantic. MCCIP Science Review, 2020, pp.322-353.

Edwards, M., Bresnan, E., Cook, K., Heath, M., Helaouet, P., Lynam, C., Raine, R. and Widdicombe, C., 2013. Impacts of climate change on plankton. MCCIP Science Review, 2013, pp.98-112.

Edwards, M., M. Heath and A. McQuatters-Gollop, 2011. Plankton in MCCIP Annual Report Card 2010-11, MCCIP Science Review, p.10.

Engelhard, G.H., Righton, D.A. and Pinnegar, J.K., 2014. Climate change and fishing: a century of shifting distribution in North Sea cod. *Global Change Biology*, 20(8), p.2473-2483.

Epstein, G., Middelburg, J.J., Hawkins, J.P., Norris, C.R. and Roberts, C.M. (2022) The impact of mobile demersal fishing on carbon storage in seabed sediments. *Global Change Biology* 28, 2875-2894.

Epstein, G. and Roberts, C.M., 2023. Does biodiversity-focused protection of the seabed deliver carbon benefits? A UK case study. *Conservation Letters*, 16(1), p.e12929.

EUMOFA (European Market Observatory for Fisheries and Aquaculture Products) 2023. Fishery Landings Comparison between countries. https://eumofa.eu/data#landingsTab

Fernandes, J.A., Papathanasopoulou, E., Hattam, C., Queirós, A.M., Cheung, W.W., Yool, A., Artioli, Y., Pope, E.C., Flynn, K.J., Merino, G. and Calosi, P., 2016. Estimating the ecological, economic and social impacts of ocean acidification and warming on UK fisheries. Fish and *Fisheries*, 18(3), pp.389-411.

Findlay, H.S., Artoli, Y., Birchenough, S.N.R., Hartman, S., León, P. and Stiasny, M., 2022. Ocean Acidification around the UK and Ireland. MCCIP Science Review 2022.

Forster, J., Hirst, A.G. and Atkinson, D., 2012. Warming-induced reductions in body size are greater in aquatic than terrestrial species. *Proceedings of the National Academy of Science*. 109, p.19310–19314. https://doi.org/10.1073/pnas.1210460109

Frost, M. and Diele, K., 2022. Essential spawning grounds of Scottish herring: current knowledge and future challenges. *Reviews in Fish Biology and Fisheries*, 32(3), pp.721-744.

Gaines, S.D., Costello, C., Owashi, B., Mangin, T., Bone, J., Molinos, J.G., Burden, M., Dennis, H., Halpern, B.S., Kappel, C.V. and Kleisner, K.M., 2018. Improved fisheries management could offset many negative effects of climate change. *Science Advances*, *4*(8), p.eaao1378.

Grafton, R.Q., Squires, D. and Steinshamn, S.I., 2023. Towards resilience-based management of marine capture fisheries. *Economic Analysis and Policy*, 77, pp.231-238.

Gullestad, P., Sundby, S. and Kjesbu, O.S., 2020. Management of transboundary and straddling fish stocks in the Northeast Atlantic in view of climate-induced shifts in spatial distribution. *Fish* ,21. P.1008–1026. https://doi.org/10.1111/faf.12485

Harte, M., Tiller, R., Kailis, G. and Burden, M., 2019. Countering a climate of instability: the future of relative stability under the Common Fisheries Policy. *ICES Journal of Marine Science*, 76(7), pp.1951-1958.

HM Government, 2022. UK Climate Change Risk Assessment 2022. Presented to Parliament pursuant to Section 56 of the Climate Change Act 2008. https://www.gov.uk/government/publications/uk-climate-change-risk-assessment-2022

Holland, M.M., Louchart, A., Artigas, L.F., Ostle, C., Atkinson, A., Rombouts, I., Graves, C.A., Devlin, M., Heyden, B., Machairopoulou, M. and Bresnan, E., 2023. Major declines in NE Atlantic plankton contrast with more stable populations in the rapidly warming North Sea. *Science of The Total Environment*, 898, p.1-11.

Hopkins, C.R., Bailey, D.M. and Potts, T., 2016. Scotland's Marine Protected Area network: reviewing progress towards achieving commitments for marine conservation. *Marine Policy*, 71, pp.44-53.

Hoppit, G., Schmidt, D.N., Brazier, P., Mieszkowska, N. and Pieraccini, M., 2022. Are marine protected areas an adaptation measure against climate change impacts on coastal ecosystems? A UK case study. *Nature-Based Solutions*, 2, p.100030.

Howarth, L.M., 2012. Exploring the fishery and ecological effects of Lamlash Bay no-take zone. Science report for Community of Arran Seabed Trust.

Huang, M., Ding, L., Wang, J., Ding, C. and Tao, J., 2021. The impacts of climate change on fish growth: A summary of conducted studies and current knowledge. *Ecological Indicators*, 121, p.106976.

Hughes, K.M., Dransfeld, L. and Johnson, M.P., 2014. Changes in the spatial distribution of spawning activity by north-east Atlantic mackerel in warming seas: 1977–2010. *Marine Biology*, 161. P.2563–2576. http://dx.doi.org/10.1007/s00227-014-2528-1

Hunter, A., Speirs, D.C. and Heath, M.R., 2019. Population density and temperature correlate with long-term trends in somatic growth rates and maturation schedules of herring and sprat. *PloS One*, 14(3), p.e0212176.

ICES, 2021. Data for OSPAR request on the production of spatial data layers of fishing intensity/pressure. Data outputs. Dataset. https://doi.org/10.17895/ices.data.8294

ICES, 2023. Integrated Ecosystem Assessments Steering Group. https://www.ices.dk/community/groups/Pages/IEASG.aspx

Ikpewe, I.E., Baudron, A.R., Ponchon, A. and Fernandes, P.G., 2021. Bigger juveniles and smaller adults: Changes in fish size correlate with warming seas. *Journal of Applied Ecology*, 58(4), p.847-856.

Jansen, T., and Gislason, H., 2011. Temperature affects the timing of spawning and migration of North Sea mackerel. *Continental Shelf Research*, 31(1), p.64-72.

JNCC, 2021. North-West Orkney MPA. https://jncc.gov.uk/our-work/north-west-orkney-mpa

Jones, M. C., Dye, S. R., Pinnegar, J. K., Warren, R., and Cheung, W. W., 2015. Using scenarios to project the changing profitability of fisheries under climate change. *Fish and Fisheries*, 16(4), p.603-622.

Kamenos, N.A., Moore, P.G. and Hall-Spencer, J.M., 2004a. Nursery-area function of maerl grounds for juvenile queen scallops Aequipecten opercularis and other invertebrates. *Marine Ecology Progress Series*, 274, p.183-189.http://www.int-res.com/abstracts/meps/v274/p183-189/.

Kamenos, N.A., Moore, P.G. and Hall-Spencer, J.M., 2004b. Small-scale distribution of juvenile gadoids in shallow inshore waters; what role does maerl play?. *ICES Journal of Marine Science*, 61(3), pp.422-429. https://doi.org/10.1016/j.icesjms.2004.02.004

Kaschner, K., J. Rius-Barile, K. Kesner-Reyes, C. Garilao, S.O. Kullander, T. Rees, T. and Froese, R., 2010. AquaMaps: Predicted range maps for aquatic species. World wide web electronic publication. https://www.aquamaps.org/

Kemp, P.S., Subbiah, G., Barnes, R., Boerder, K., O'Leary, B.C., Stewart, B.D. and Williams, C., 2023. The future of marine fisheries management and conservation in the United Kingdom: Lessons learnt from over 100 years of biased policy. *Marine Policy*, 147, p.105075.

Kristiansen, T., Stock, C., Drinkwater, K.F. and Curchitser, E.N., 2014. Mechanistic insights into the effects of climate change on larval cod. *Global Change Biology*, 20(5), p.1559-1584.

Kühn, B., Kempf, A., Brunel, T., Cole, H., Mathis, M., Sys, K., Trijoulet, V., Vermard, Y. and Taylor, M., 2023. Adding to the mix–Challenges of mixed-fisheries management in the North Sea under climate change and technical interactions. *Fisheries Management and Ecology*, 30, p.360-377.

Lindegren, M., Möllmann, C., Nielsen, A., Brander, K., MacKenzie, B.R. and Stenseth, N.C., 2010. Ecological forecasting under climate change: the case of Baltic cod. *Proceedings of the Royal Society B: Biological Sciences*, 277(1691), pp.2121-2130.

Marine Scotland, 2023. National Marine Plan Interactive. https://marinescotland.atkinsgeospatial.com/nmpi/

Marshall, C. T., Baudron, A. R., Fallon, N. G. and Spencer, P., (2019). FIS workshop on Global synthesis of climate impacts on fish distribution and growth and implications for Scottish fisheries: FIS028. A Study Commissioned by Fisheries Innovation Scotland (FIS), https://fisorg.uk/

Mason, J.G., Woods, P.J., Thorlacius, M., Guðnason, K., Saba, V.S., Sullivan, P.J. and Kleisner, K.M., 2021. Projecting climate-driven shifts in demersal fish thermal habitat in Iceland's waters. *ICES Journal of Marine Science*, 78(10), p.3793-3804.

Maureaud, A., Frelat, R., Pécuchet, L., Shackell, N., Mérigot, B., Pinsky, M.L., Amador, K., Anderson, S.C., Arkhipkin, A., Auber, A. and Barri, I., 2020. Are we ready to track climate-driven shifts in marine species across international boundaries? -A global survey of scientific bottom trawl data. *Global Change Biology*, 27(2), p.220-236.

McQueen, K. and Marshall, C. T., 2017. Shifts in spawning phenology of cod linked to rising sea temperatures, *ICES Journal of Marine Science*, 74 (6). P.1561–1573. https://doi.org/10.1093/icesjms/fsx025

McGeady, R., Lordan, C. and Power, A.M., 2021. Shift in the larval phenology of a marine ectotherm due to ocean warming with consequences for larval transport. *Limnology and Oceanography*, 66(2), pp.543-557.

Moffat, C., Baxter, j., Berx, B., Bosley, K., Boulcott, P., Cox, M., Cruickshank, L., Gillham, K., Cox, A., Haynes, V., Roberts, A., Vaughan, D., and Webster, L., 2020. Scotland's Marine Assessment 2020. Scottish Government.

Montero-Serra, I., Edwards, M. and Genner, M.J., 2015 Warming shelf seas drive the subtropicalization of European pelagic fish communities. *Global Change Biology*, 21, p.144–153.

Núnez-Riboni, I., Taylor, M. H., Kempf, A., Püts, M., and Mathis, M., 2019. Spatially resolved past and projected changes of the suitable thermal habitat of North Sea cod (Gadus morhua) under climate change. *ICES Journal of Marine Science*, 76(7), p.2389-2403.

Ojea, E., Pearlman, I., Gaines, S.D. and Lester, S.E., 2016. Fisheries regulatory regimes and resilience to climate change. *Ambio*, 46, pp.399-412.

Ojea, E., Fontán, E., Fuentes-Santos, I. and Bueno-Pardo, J., 2021. Assessing countries' social-ecological resilience to shifting marine commercial species. *Scientific Reports*, 11(1), p.22926.

Olin, A.B., Banas, N.S., Johns, D.G., Heath, M.R., Wright, P.J. and Nager, R.G., 2022. Spatio-temporal variation in the zooplankton prey of lesser sandeels: species and community trait patterns from the Continuous Plankton Recorder. *ICES Journal of Marine Science*, 79(5), p.1649-1661.

OSPAR, 2023. Pelagic Habitats Thematic Assessment. In: OSPAR, 2023: Quality Status Report 2023. OSPAR Commission, London. Available at: https://oap.ospar.org/en/ospar-assessments/quality-status-reports/qsr-2023/thematic-assessments/pelagic-habitats/

Payne, M.R., Kudahl, M., Engelhard, G.H., Peck, M.A. and Pinnegar, J.K., 2021. Climate risk to European fisheries and coastal communities. *Proceedings of the National Academy of Sciences*, 118(40), p.e2018086118.

Pinnegar, J.K., Buckley, P. and Engelhard, G.H., 2017. Impacts of climate change in the United Kingdom and Ireland. Climate Change Impacts on Fisheries and Aquaculture: A Global Analysis, 1, p.381-413. https://doi.org/10.1002/9781119154051.ch12

Pinnegar, J.K., Cheung, W.W., Jones, M., Merino, G., Turrell, B. and Reid, D., 2013. Impacts of climate change on fisheries. MCCIP Sci Rev, 2013, p.302-317.

Pinsky, M.L., Fenichel, E., Fogarty, M., Levin, S., McCay, B., St. Martin, K., Selden, R.L. and Young, T., 2020. Fish and fisheries in hot water: What is happening and how do we adapt?. *Population Ecology*, 63(1), p.17-26.

Pitois, S.G., Lynam, C.P., Jansen, T., Halliday, N. and Edwards, M., 2012. Bottom-up effects of climate on fish populations: data from the Continuous Plankton Recorder. *Marine Ecology Progress Series*, 456, p.169-186. https://doi.org/10.3354/meps09710

Prokešová, M., Gebauer, T., Matouˇsek, J., Lundov´a, K., ˇCejka, J., Zuskov´a, E. and Stejskal, V., 2020. Effect of temperature and oxygen regime on growth and physiology of juvenile *Salvelinus fontinalis* × *Salvelinus alpinus* hybrids. *Aquaculture*, 522, p. e735119. https://doi.org/10.1016/j.aquaculture.2020.735119

Régnier, T., Gibb, F.M. and Wright, P.J.,2017. Importance of trophic mismatch in a winter-hatching species: evidence from lesser sandeel. *Marine Ecology Progress Series,* 567, p.185-197.

Régnier, T., Gibb, F.M. and Wright, P.J., 2019. Understanding temperature effects on recruitment in the context of trophic mismatch. *Scientific Reports*, 9(1), p.15179.

Rindorf, A., Gislason, H., Burns, F., Ellis, J.R. and Reid, D., 2020. Are fish sensitive to trawling recovering in the Northeast Atlantic? *Journal of Applied Ecology*, 57(10), pp.1936-1947.

Rindorf, A., Mumford, J., Baranowski, P., Clausen, L.W., García, D., Hintzen, N.T., Kempf, A., Leach, A., Levontin, P., Mace, P. and Mackinson, S., 2017. Moving beyond the MSY concept to reflect multidimensional fisheries management objectives. *Marine Policy*, 85, pp.33-41.

Ryan M, R. and Bailey D, M, 2012. Trawling and dredging in the Clyde sea area: history, impacts and prospects for Recovery. University of Glasgow

Schmidt, D.N., Pieraccini, M. and Evans, L., 2022. Marine protected areas in the context of climate change: key challenges for coastal social-ecological systems. *Philosophical Transactions of the Royal Society B*, *Biological Sciences*, 377(1854), p.20210131.

Scottish Government, 2020. Scotland's Fisheries Management Strategy 2020-2030. https://www.gov.scot/publications/scotlands-future-fisheries-management-strategy-2020-2030/

Scottish Government, 2022. Scottish Sea Fisheries Statistics 2021. https://www.gov.scot/publications/scottish-sea-fisheries-statistics-2022/

Scottish Government, 2024. Climate change – national adaptation plan 2024 to 2029: consultation. https://www.gov.scot/publications/public-consultation-scottish-national-adaptation-plan-2024-2029/pages/3/

SeaFish, 2023. UK Seafood Trade and Tariff Tool. https://public.tableau.com/app/profile/seafish/viz/SeafishTradeandTariffTool/Overview

Serpetti, N., Baudron, A.R., Burrows, N.T., Payne, B.L., Helaouet, P., Fernandes, P.G. and Heymans, J.J., 2017. Impact of ocean warming on sustainable fisheries management informs the Ecosystem Approach to Fisheries. *Scientific Reports*, 7(1), p.134-138.

Simon-Nutbrown, C., Hollingsworth, P.M., Fernandes., T.F., Kamphausen, L., Baxter, J.M. and Burdett, H.L., 2020 Species distribution modelling predicts significant declines in coralline algae populations under projected climate change with implications for conservation policy. *Frontiers in Marine Science* 7, p.1–14. https://doi.org/10.3389/fmars.2020.575825

Simpson, S. D., Blanchard, J. L., and Genner, M. G., 2013. Impacts of climate change on fish. MCCIP. 2013: p. 113-124.

Simpson, S. D., Jennings, S., Johnson, M. P., Blanchard, J. L., Schön, P. J., Sims, D. W., and Genner, M. J., 2011. Continental shelf-wide response of a fish assemblage to rapid warming of the sea. *Current Biology*, 21(18), p.1565-1570.

Stewart, B.D., Howarth, L.M., Wood, H., Whiteside, K., Carney, W., Crimmins, É., O'Leary, B.C., Hawkins, J.P. and Roberts, C.M., 2020. Marine conservation begins at home: how a local community and protection of a small bay sent waves of change around the UK and beyond. *Frontiers in Marine Science*, 7, p.76.

Stobart, B., Warwick, R., González, C., Mallol, S., Díaz, D., Reñones, O. and Goñi, R., 2009. Long-term and spillover effects of a marine protected area on an exploited fish community. *Marine Ecology Progress Series*, 384, pp.47-60.

Stoker, B., Turrell, W.R., Robinson, K., Howes, E., Buckley, P.J., Maltby, K. and Matear, L., 2020. *Marine Climate Change Impacts*: Report Card 2020.

Townhill, B.L., Couce, E., Tinker, J., Kay, S. and Pinnegar, J.K., 2023. Climate change projections of commercial fish distribution and suitable habitat around north western Europe. *Fish and Fisheries*, 24(5), pp.848-862.

Townhill, B.L., Pinnegar, J.K., Righton, D.A. and Metcalfe, J.D., 2017. Fisheries, low oxygen and climate change: how much do we really know?. *Journal of Fish Biology*, 90(3), p.723-750.

Travers-Trolet, M., Bourdaud, P., Genu, M., Velez, L. and Vermard, Y., 2020. The risky decrease of fishing reference points under climate change. *Frontiers in Marine Science*, 7, p.568232.

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, p. 2285–2298. https://doi.org/10.1111/jbi.12847

Van Leeuwen, S.M., Le Quesne, W.F. and Parker, E.R., 2016. Potential future fisheries yields in shelf waters: a model study of the effects of climate change and ocean acidification. *Biogeosciences*, 13(2), p.441-454.

Wilson, K.L., Tittensor, D.P., Worm, B. and Lotze, H.K., 2020. Incorporating climate change adaptation into marine protected area planning. *Global Change Biology*, 26(6), p.3251-3267.

Winter, A.M., Richter, A. and Eikeset, A.M., 2020. Implications of Allee effects for fisheries management in a changing climate: evidence from Atlantic cod. *Ecological Applications*, 30(1), p.e01994.

Winne, S., Pritchard, A., Kennedy, S., and O'Gorman, S., 2022. Review of climate vulnerability assessment of Scotland's marine environment and marine economy. https://www.climatexchange.org.uk/projects/review-of-climate-vulnerability-assessment-of-scotlands-marine-environment-and-marine-economy/

Wright, P.J., Orpwood, J.E. and Boulcott, P., 2017. Warming delays ovarian development in a capital breeder. *Marine Biology*, 164, pp.1-9.

Wright, P.J., Pinnegar, J.K. and Fox, C.J., 2020. Impacts of climate change on fish, relevant to the coastal and marine environment around the UK. MCCIP Science Review 2020, 354–381.

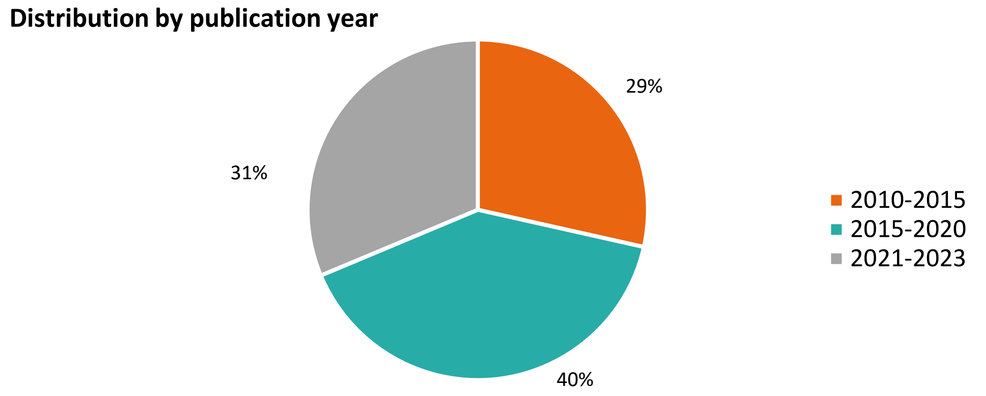
7 Appendices

7.1 Appendix A: Methodological Approach

Key Words	Key species
Fisheries and Scotland and climate risk resilience policy and climate change	Cod
Climate change and distribution shifts and Scotland and cod or herring	Haddock
Climate change and distribution shifts and Scotland and hake or mackerel	Hake
Climate change and distribution shifts and Scotland and blue whiting or haddock	Herring
Monkfish or angler fish and climate change and UK	Mackerel
Climate change and distribution shifts and Scotland and saithe	*Nephrops*
Climate change and distribution shifts and *Nephrops*	Monkfish (or anglerfish)
Climate change and Scotland and sandeels or plankton	Saithe
Blue economy or marine economy and fisheries and Scotland and climate change	Whiting
MPA and fisheries and Scotland and climate risk resilience policy or climate change	
Climate change and Scotland and fisheries and plankton and bottom up control	
Ocean acidification and climate change and fisheries and Scotland	
Climate change and Scotland and risk to marine habitats or marine species	
Shifting commercial species or sustainable fisheries management and climate risk resilience policy and Scotland	
Maladaptation and Lock In and UK	

Overall, 212 documents were identified with potential relevance to the current study. These sources were reassessed in line with the inclusion criteria by CXC and BMT and rated accordingly. A spread of this literature covering multiple regions and years is broken down in Figure 1. Following the literature ratings, a list of 150 of the identified sources were given priority for the purpose of this report following screening.

As a note, studies were assessed against the aims of this paper, not against the authors own aims. Many of the studies assessed, while partially relevant to our study, focused on specific aspects of fisheries, such as environmental impacts or future distribution predictions. As such, there are identified limitations of each source with respect to how each source aligns with this paper’s assessment parameters and research questions.



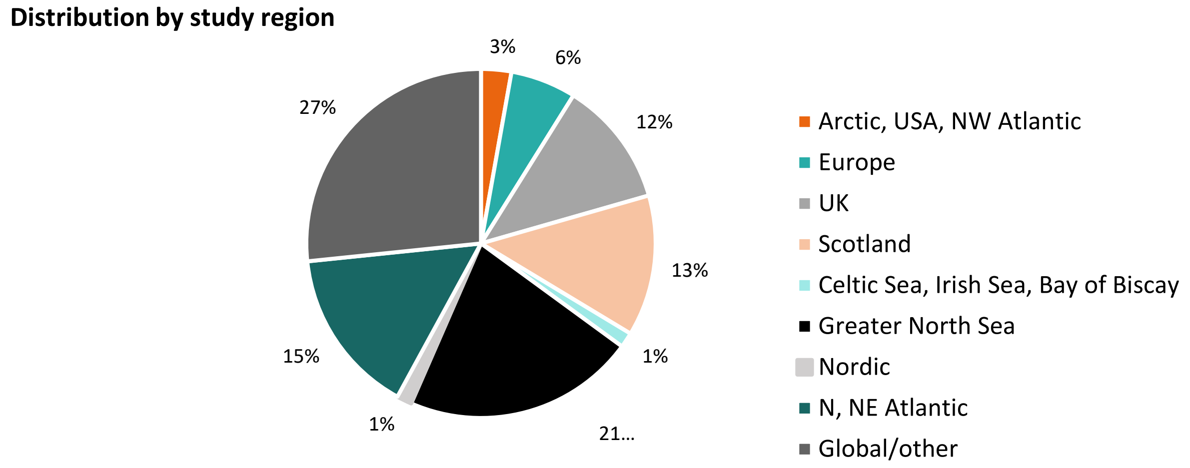


Figure 1: Number of literature sources included as part of the study by region and year

Scoring was done for each source according to their quality based on five questions: (a) what is the sample/study population, (b) research design and methodology of the source, (c) interpretation of the results, (d) limitations of the study, and (e) level of uncertainty. The significance was then calculated based on the year of publication (5%) study type (observed or predictive) (5%) relevance of the paper (75%) and the number of research questions answered (15%). Sources were given a score for significance of High (<75%) Medium (75-60%) or Low (>60). The level of confidence was then calculated using the scores from quality and significance and the formula C=f(QS,).

An online workshop was conducted by the project team on 7th September 2023 a total of nineteen delegates from the fishing industry, regulatory and advisory bodies, and research community were invited; of these, nine attended the workshop, representing the following organisations: Scottish Government, CEFAS, JNCC, SEPA, University of Aberdeen, University of the Highlands and Islands, Seafish and the Scottish Whitefish Producers Association. The workshop was run over four hours, with discussion of the five main questions posed as the focus of this study.

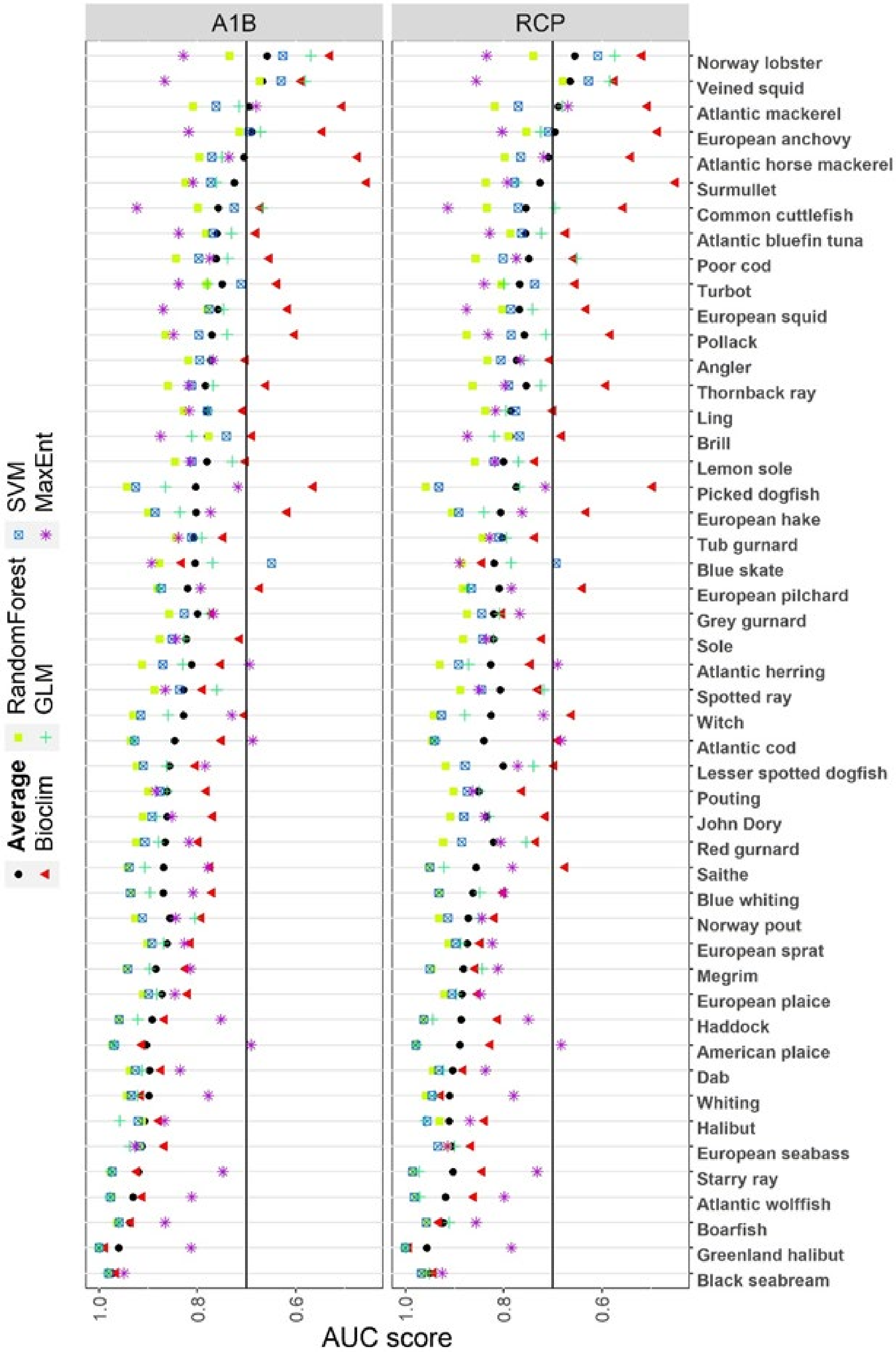
7.2 Appendix B: Predictive habitat suitability maps

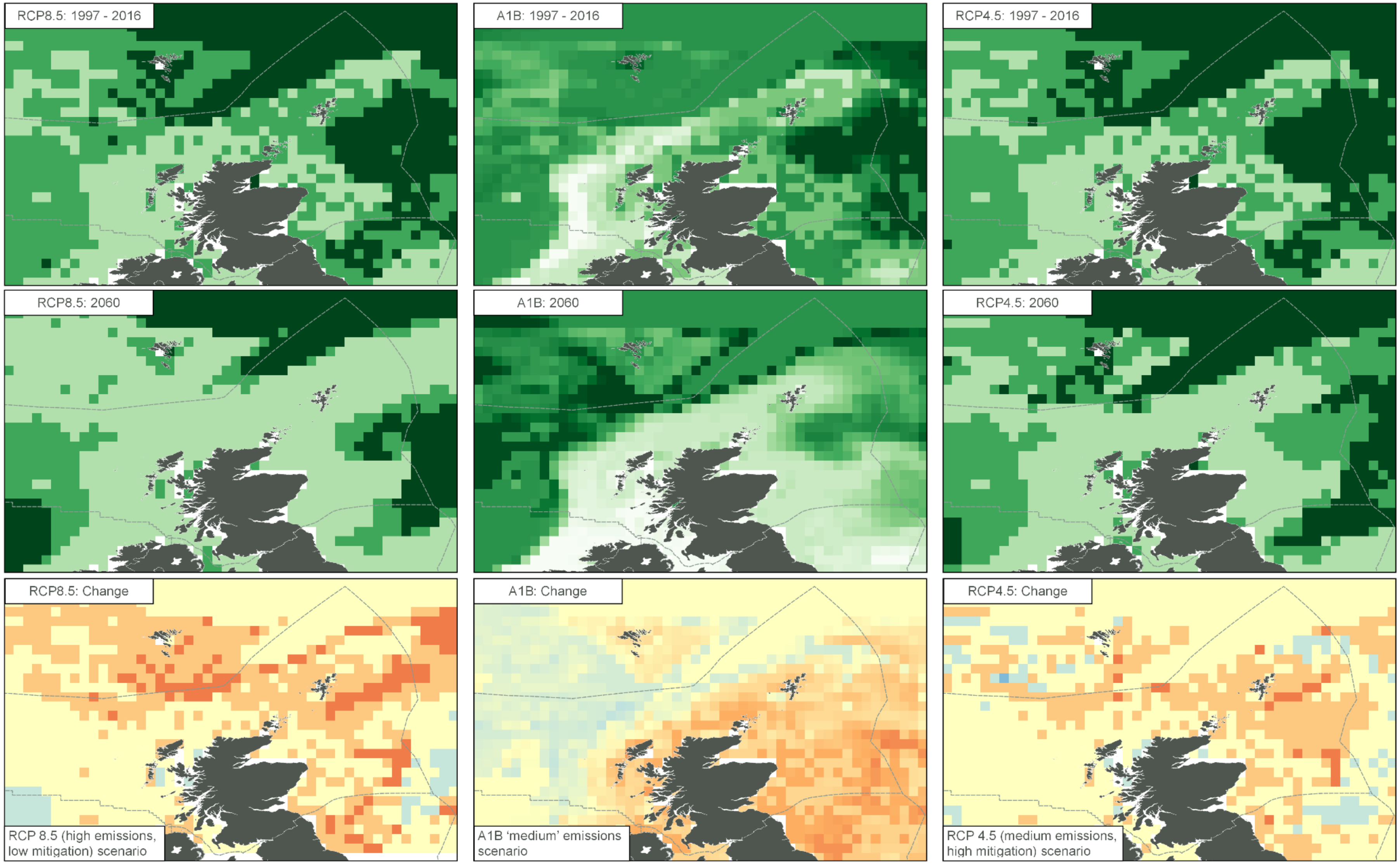
The data presented below regarding habitat suitability for economically significant fish species in the UK are derived from modelling outputs produced by Townhill et al. (2023). While predictive models may not forecast the future with absolute precision, they offer valuable insights into potential outcomes under various emissions scenarios, aiding in the understanding of potential future developments in the marine environment. This information is instrumental in guiding decision-making and formulating strategies to mitigate risks and optimize opportunities.

The authors selected 49 species for habitat suitability analysis, consulting with scientists and policymakers. The species list includes those currently of commercial importance in the UK, as well as some warm-water species significant in France and Spain but not yet in the United Kingdom. The term 'habitat suitability' refers to bathymetry and environmental hydrographic conditions (temperature and salinity) that are suitable for each species, excluding bottom substrate characteristics (due to insufficient regional data) and local species interactions within communities (eg food availability). The study utilized data from the training period of 1997 to 2016 to determine the current habitat suitability of each species, and models were run to calculate 20-year averages from 2010 to 2070.

Climate projections were based on three different future carbon emissions trajectories from two sources: the A1B 'medium' emissions scenario from the Coupled Model Intercomparison Project (CMIP) 3 Special Report Emissions Scenarios (SRES) dataset, and the CMIP5 Representative Concentration Pathway (RCP) 4.5 (medium emissions, high mitigation) and 8.5 (high emissions, low mitigation) projections. The A1B model, used in the IPCC Fourth Assessment Report (AR4), envisions rapid economic growth, a global population peaking at 9 billion in 2050, technological advancements, and global convergence in income and lifestyle. The Representative Concentration Pathways (RCPs) was used in the IPCC Fifth Assessment Report (AR5) in 2014. RCP 4.5 is considered an intermediate scenario, while RCP 8.5 is a basis for a worst case climate change scenario thought to be very unlikely, but still possible as feedbacks are not well understood.

Despite using the same datasets and geographic regions in the modelling, habitat suitability outputs for the training period (1997-2016) differed between the RCP and A1B scenarios. The authors employed a comprehensive approach, utilizing multiple models and climate change scenarios. While there were variations in the magnitude of change among models, and certain models performed better for specific species, overall trends in habitat suitability and abundance were consistent across models and climate scenarios. This underscores the importance of employing an ensemble approach, using multiple modelling techniques with diverse climate scenarios to address the uncertainties in climate change projections. The ensemble approach, incorporating five different models, resulted in varying averaged habitat suitability projections for this period, with only Area Under the Curve (AUC) values exceeding 0.7 included in the outputs.


A1B
RCP
Norway lobster
Veined squid
Atlantic mackerel
European anchovy
Atlantic horse mackerel
Surmullet
Common cuttlefish
Atlantic bluefin tuna
Poor cod
Turbot
European squid
Pollack
Angler
Thornback ray
Ling
Brill
Lemon sole
Picked dogfish
European hake
Tub gurnard
Blue skate
European pilchard
Grey gurnard
Sole
Atlantic herring
Spotted ray
Witch
Atlantic cod
Lesser spotted dogfish
Pouting
John Dory
Red gurnard
Saithe
Blue whiting
Norway pout
European sprat
Megrim
European plaice
Haddock
American plaice
Dab
Whiting
Halibut
European seabass
Starry ray
Atlantic wolffish
Boarfish
Greenland halibut
Black seabream
1.0
0.8
0.6
AUC score
Average
Bioclim
RandomForest
GLM
SVM
MaxEnt



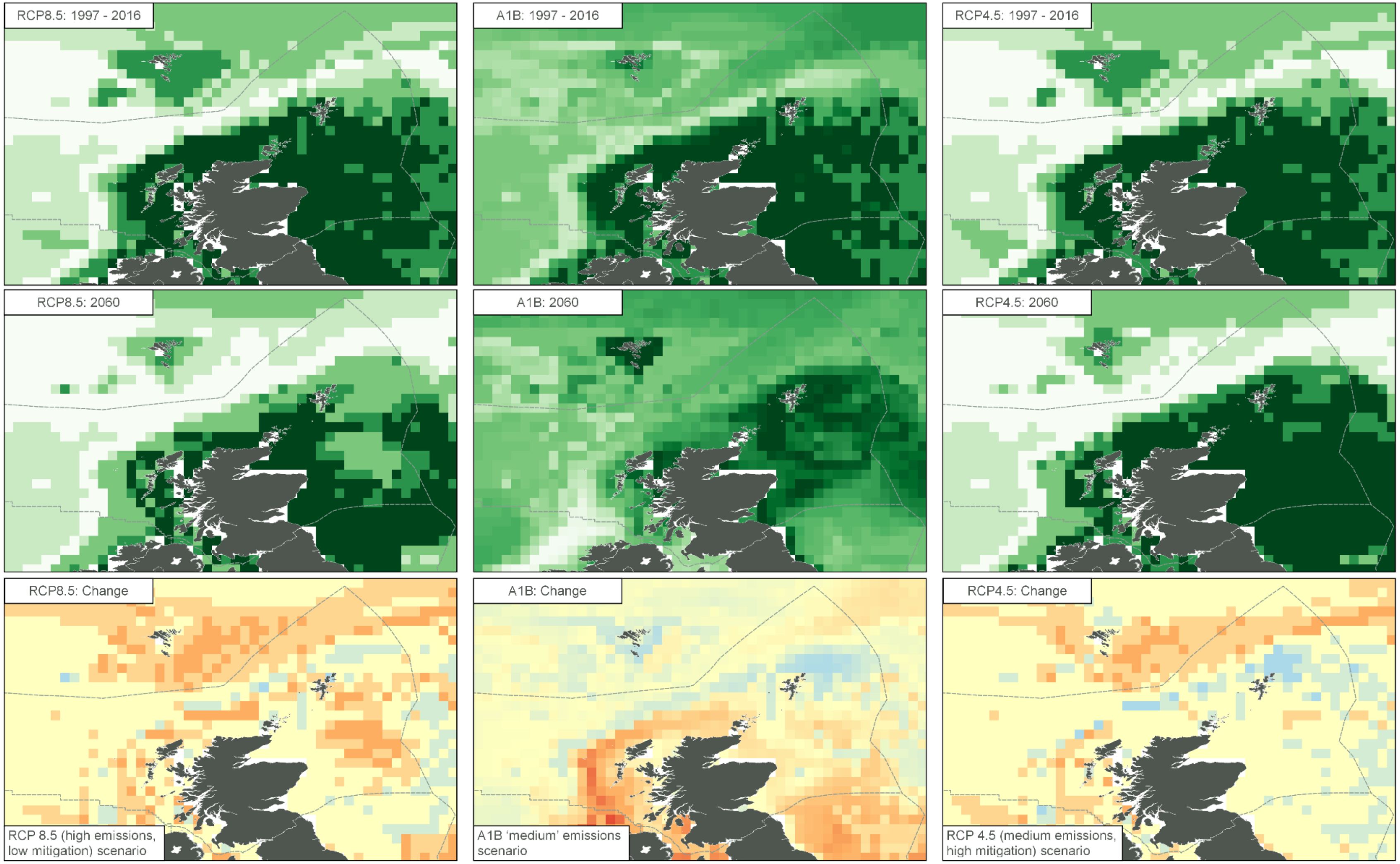
Townhill et al., 2023: Change in habitat suitability, under all modelled climate projections, in Scottish waters (Present day to 2060): Atlantic cod (Gadus morhua, Gadidae)

RCP 8.5 and 4.5 emissions scenarios derived from the Coupled Model Intercomparison Project (CMIP) 5 Representative Concentration Pathway (RCP) 8.5 (high emissions, low mitigation) and 4.5 (medium emissions, high mitigation) projections. A1B medium emissions scenario derived from CIMP3 Special Report Emissions Scenario (SRES) A1B projection. The training period of 1997 to 2016 (Present Day) was used to determine each species current habitat suitability, and the models run was used to calculate 20-year averages from 2010 to 2070. The ensemble approach, incorporating five different models, resulted in varying averaged habitat suitability projections for this period, with only AUC values exceeding 0.7 included in the outputs.
Number of ENM models with acceptable performance (i.e. AUC score of 0.7 or above): 3

Townhill, B. L., Couce, E., Tinker, J., Kay, S., & Pinnegar, J. K. (2023). Climate change projections of commercial fish distribution and suitable habitat around north western Europe. Fish and Fisheries.

Habitat Suitability: 1 – 0

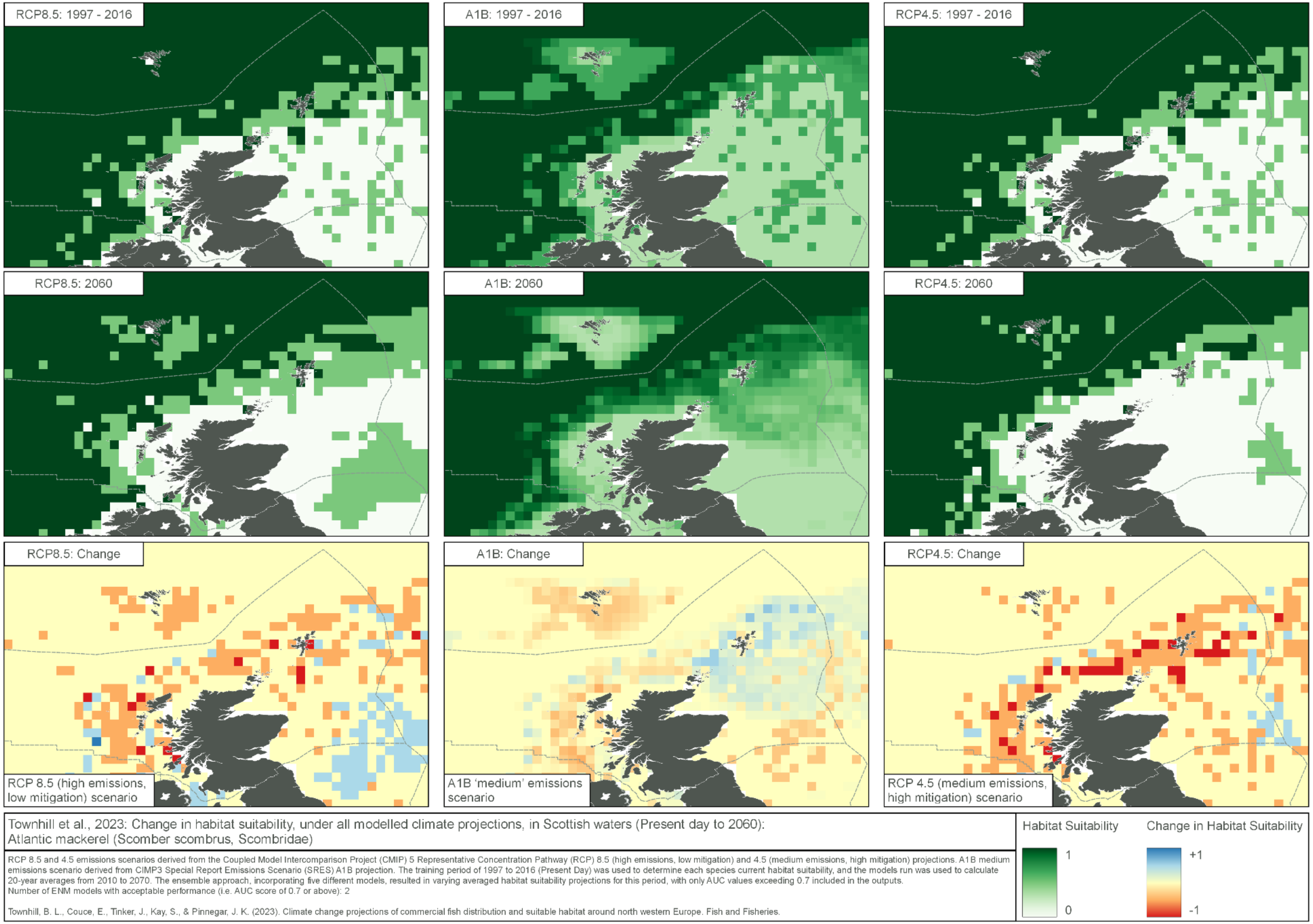
Change in Habitat Suitability: +1 – -1



Townhill et al., 2023: Change in habitat suitability, under all modelled climate projections, in Scottish waters (Present day to 2060): Atlantic herring (Clupea harengus, Clupeidae)

RCP 8.5 and 4.5 emissions scenarios derived from the Coupled Model Intercomparison Project (CMIP) 5 Representative Concentration Pathway (RCP) 8.5 (high emissions, low mitigation) and 4.5 (medium emissions, high mitigation) projections. A1B medium emissions scenario derived from CIMP3 Special Report Emissions Scenario (SRES) A1B projection. The training period of 1997 to 2016 (Present Day) was used to determine each species current habitat suitability, and the models run was used to calculate 20-year averages from 2010 to 2070. The ensemble approach, incorporating five different models, resulted in varying averaged habitat suitability projections for this period, with only AUC values exceeding 0.7 included in the outputs.
Number of ENM models with acceptable performance (i.e. AUC score of 0.7 or above): 4

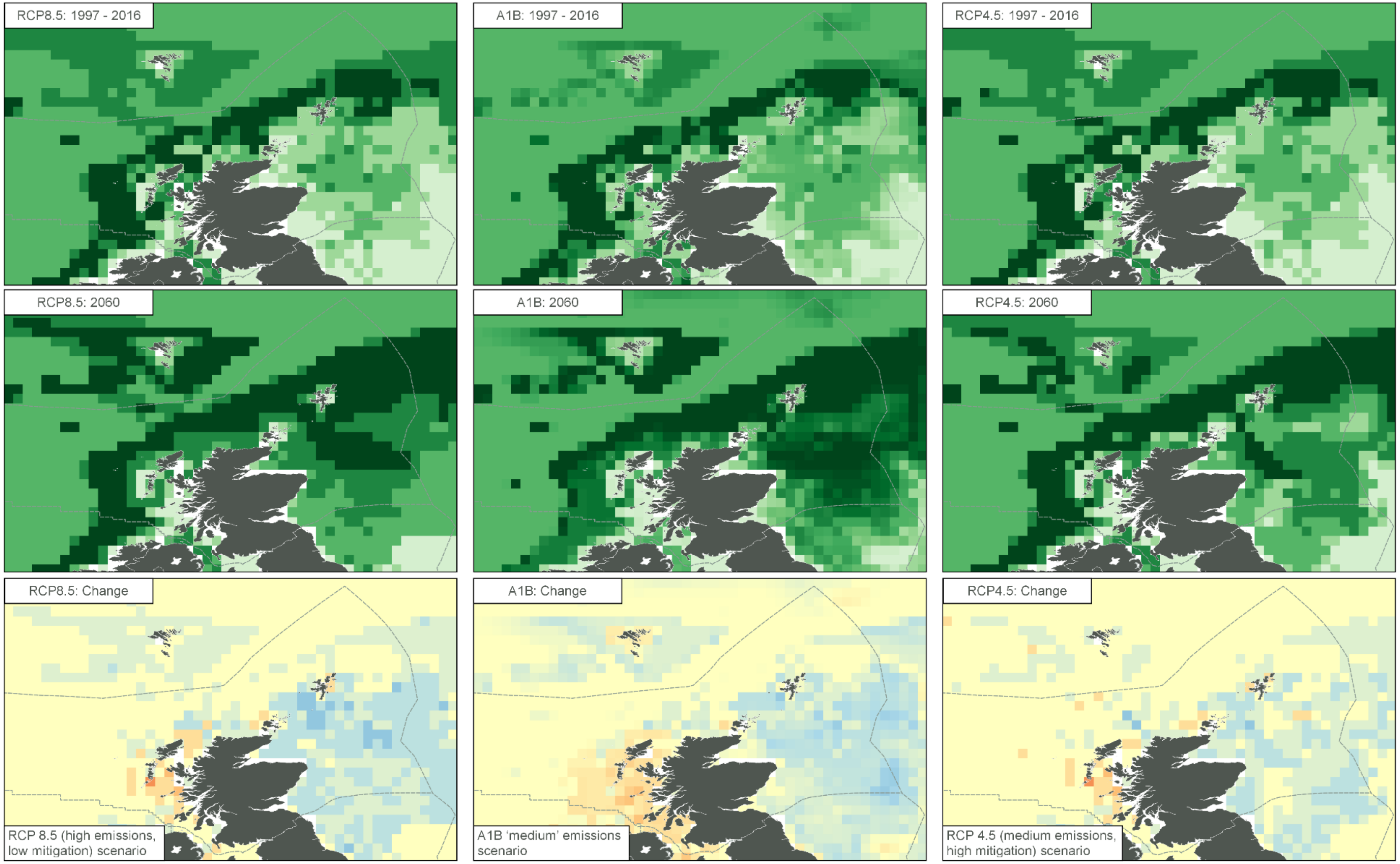
Townhill, B. L., Couce, E., Tinker, J., Kay, S., & Pinnegar, J. K. (2023). Climate change projections of commercial fish distribution and suitable habitat around north western Europe. Fish and Fisheries.



Townhill et al., 2023: Change in habitat suitability, under all modelled climate projections, in Scottish waters (Present day to 2060): Atlantic mackerel (Scomber scombrus, Scombridae)

RCP 8.5 and 4.5 emissions scenarios derived from the Coupled Model Intercomparison Project (CMIP) 5 Representative Concentration Pathway (RCP) 8.5 (high emissions, low mitigation) and 4.5 (medium emissions, high mitigation) projections. A1B medium emissions scenario derived from CIMP3 Special Report Emissions Scenario (SRES) A1B projection. The training period of 1997 to 2016 (Present Day) was used to determine each species current habitat suitability, and the models run was used to calculate 20-year averages from 2010 to 2070. The ensemble approach, incorporating five different models, resulted in varying averaged habitat suitability projections for this period, with only AUC values exceeding 0.7 included in the outputs.
Number of ENM models with acceptable performance (i.e. AUC score of 0.7 or above): 2

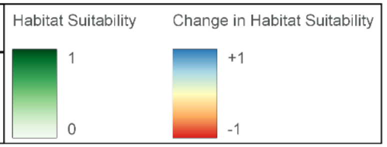
Townhill, B. L., Couce, E., Tinker, J., Kay, S., & Pinnegar, J. K. (2023). Climate change projections of commercial fish distribution and suitable habitat around north western Europe. Fish and Fisheries.

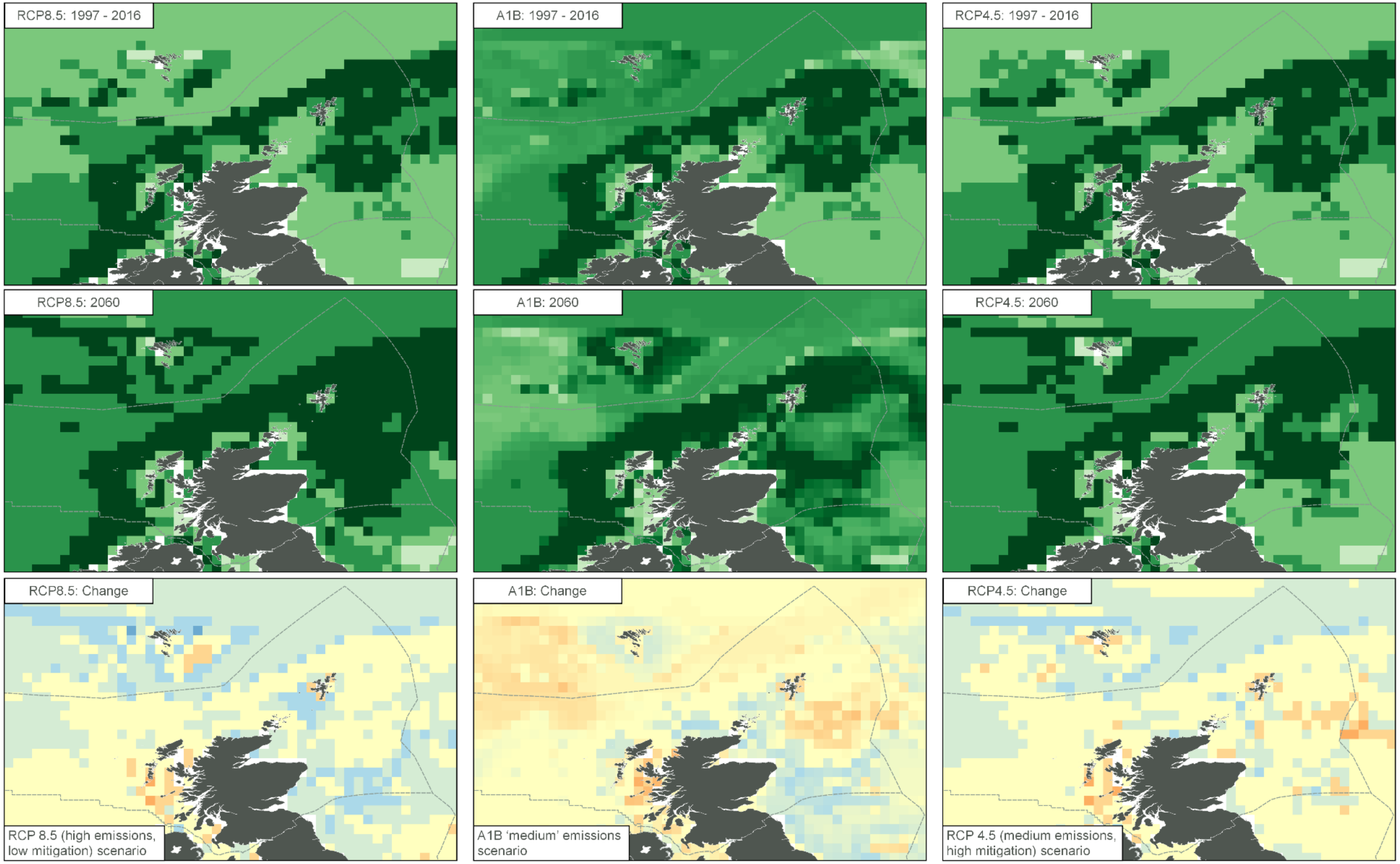


Townhill et al., 2023: Change in habitat suitability, under all modelled climate projections, in Scottish waters (Present day to 2060): Blue whiting (Micromesistius poutassou, Gadidae)

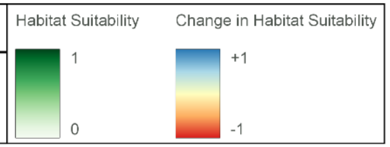
RCP 8.5 and 4.5 emissions scenarios derived from the Coupled Model Intercomparison Project (CMIP) 5 Representative Concentration Pathway (RCP) 8.5 (high emissions, low mitigation) and 4.5 (medium emissions, high mitigation) projections. A1B medium emissions scenario derived from CIMP3 Special Report Emissions Scenario (SRES) A1B projection. The training period of 1997 to 2016 (Present Day) was used to determine each species current habitat suitability, and the models run was used to calculate 20-year averages from 2010 to 2070. The ensemble approach, incorporating five different models, resulted in varying averaged habitat suitability projections for this period, with only AUC values exceeding 0.7 included in the outputs.
Number of ENM models with acceptable performance (i.e. AUC score of 0.7 or above): 5

Townhill, B. L., Couce, E., Tinker, J., Kay, S., & Pinnegar, J. K. (2023). Climate change projections of commercial fish distribution and suitable habitat around north western Europe. Fish and Fisheries.



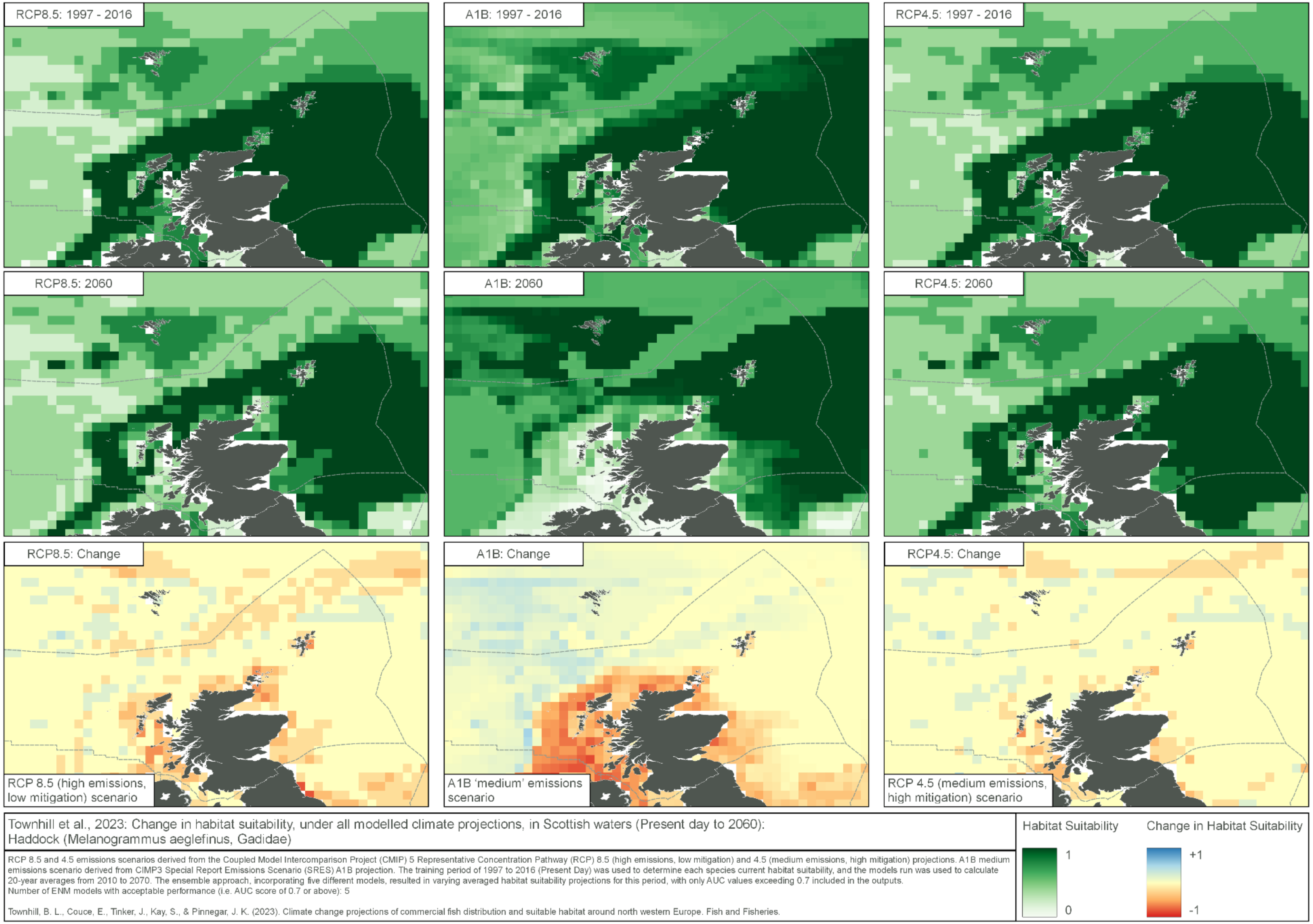


Townhill et al., 2023: Change in habitat suitability, under all modelled climate projections, in Scottish waters (Present day to 2060): European hake (Merluccius merluccius, Merlucciidae)



RCP 8.5 and 4.5 emissions scenarios derived from the Coupled Model Intercomparison Project (CMIP) 5 Representative Concentration Pathway (RCP) 8.5 (high emissions, low mitigation) and 4.5 (medium emissions, high mitigation) projections. A1B medium emissions scenario derived from CIMP3 Special Report Emissions Scenario (SRES) A1B projection. The training period of 1997 to 2016 (Present Day) was used to determine each species current habitat suitability, and the models run was used to calculate 20-year averages from 2010 to 2070. The ensemble approach, incorporating five different models, resulted in varying averaged habitat suitability projections for this period, with only AUC values exceeding 0.7 included in the outputs.
Number of ENM models with acceptable performance (i.e. AUC score of 0.7 or above): 4

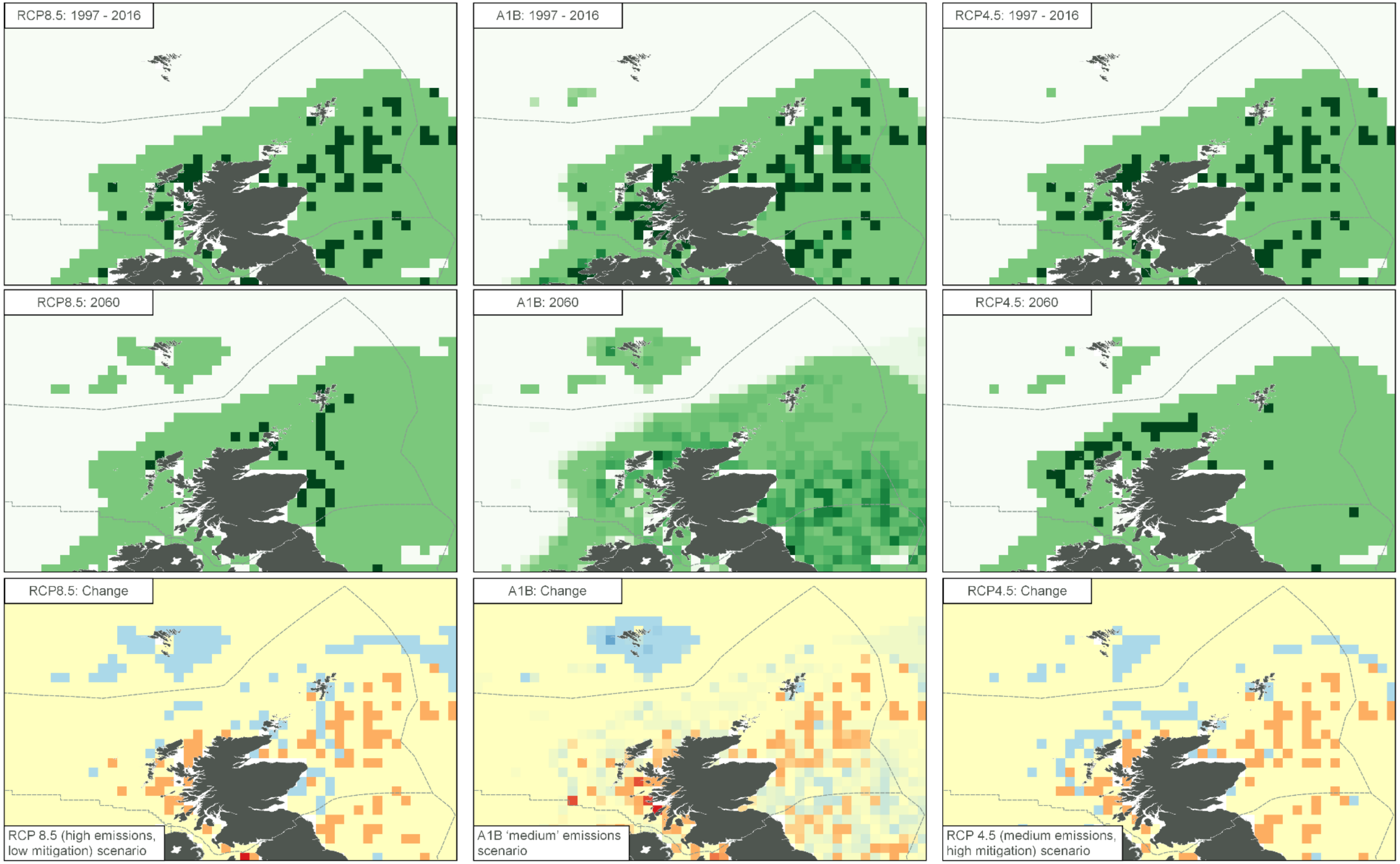
Townhill, B. L., Couce, E., Tinker, J., Kay, S., & Pinnegar, J. K. (2023). Climate change projections of commercial fish distribution and suitable habitat around north western Europe. Fish and Fisheries.



Townhill et al., 2023: Change in habitat suitability, under all modelled climate projections, in Scottish waters (Present day to 2060): Haddock (Melanogrammus aeglefinus, Gadidae)

RCP 8.5 and 4.5 emissions scenarios derived from the Coupled Model Intercomparison Project (CMIP) 5 Representative Concentration Pathway (RCP) 8.5 (high emissions, low mitigation) and 4.5 (medium emissions, high mitigation) projections. A1B medium emissions scenario derived from CIMP3 Special Report Emissions Scenario (SRES) A1B projection. The training period of 1997 to 2016 (Present Day) was used to determine each species current habitat suitability, and the models run was used to calculate 20-year averages from 2010 to 2070. The ensemble approach, incorporating five different models, resulted in varying averaged habitat suitability projections for this period, with only AUC values exceeding 0.7 included in the outputs.
Number of ENM models with acceptable performance (i.e. AUC score of 0.7 or above): 5

Townhill, B. L., Couce, E., Tinker, J., Kay, S., & Pinnegar, J. K. (2023). Climate change projections of commercial fish distribution and suitable habitat around north western Europe. Fish and Fisheries.



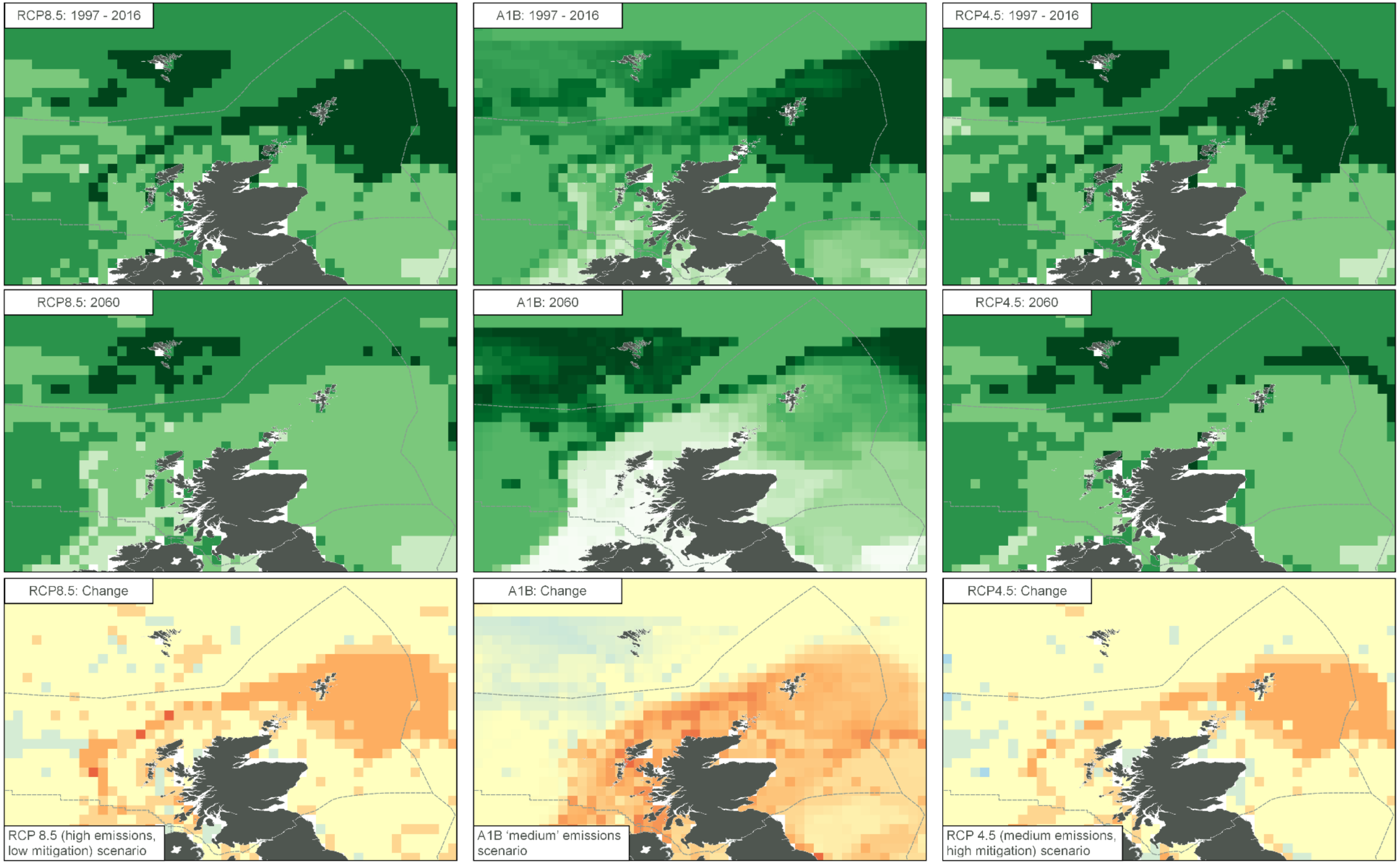
Townhill et al., 2023: Change in habitat suitability, under all modelled climate projections, in Scottish waters (Present day to 2060): Norway lobster (Nephrops norvegicus, Nephropidae)

RCP 8.5 and 4.5 emissions scenarios derived from the Coupled Model Intercomparison Project (CMIP) 5 Representative Concentration Pathway (RCP) 8.5 (high emissions, low mitigation) and 4.5 (medium emissions, high mitigation) projections. A1B medium emissions scenario derived from CIMP3 Special Report Emissions Scenario (SRES) A1B projection. The training period of 1997 to 2016 (Present Day) was used to determine each species current habitat suitability, and the models run was used to calculate 20-year averages from 2010 to 2070. The ensemble approach, incorporating five different models, resulted in varying averaged habitat suitability projections for this period, with only AUC values exceeding 0.7 included in the outputs.
Number of ENM models with acceptable performance (i.e. AUC score of 0.7 or above): 2

Townhill, B. L., Couce, E., Tinker, J., Kay, S., & Pinnegar, J. K. (2023). Climate change projections of commercial fish distribution and suitable habitat around north western Europe. Fish and Fisheries.

Habitat Suitability: 1 – 0

Change in Habitat Suitability: +1 – -1



Townhill et al., 2023: Change in habitat suitability, under all modelled climate projections, in Scottish waters (Present day to 2060): Saithe (Pollachius virens, Gadidae)

RCP 8.5 and 4.5 emissions scenarios derived from the Coupled Model Intercomparison Project (CMIP) 5 Representative Concentration Pathway (RCP) 8.5 (high emissions, low mitigation) and 4.5 (medium emissions, high mitigation) projections. A1B medium emissions scenario derived from CIMP3 Special Report Emissions Scenario (SRES) A1B projection. The training period of 1997 to 2016 (Present Day) was used to determine each species current habitat suitability, and the models run was used to calculate 20-year averages from 2010 to 2070. The ensemble approach, incorporating five different models, resulted in varying averaged habitat suitability projections for this period, with only AUC values exceeding 0.7 included in the outputs.
Number of ENM models with acceptable performance (i.e. AUC score of 0.7 or above): 4

Townhill, B. L., Couce, E., Tinker, J., Kay, S., & Pinnegar, J. K. (2023). Climate change projections of commercial fish distribution and suitable habitat around north western Europe. Fish and Fisheries.

climate X change

Scotland's centre of expertise connecting climate change research and policy

info@climatexchange.org.uk
+44(0)131 651 4783
@climatexchange_
www.climatexchange.org.uk

ClimateXChange, Edinburgh Climate Change Institute, High School Yards, Edinburgh EH1 1LZ

If you require the report in an alternative format such as a Word document, please contact info@climatexchange.org.uk **or 0131 651 4783.**