Climate Change Impacts on Commercial and Recreational Fisheries Relevant to the UK and Ireland

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KEY FACTS

What is already happening?

- Many recent studies have characterised shifts in the distribution of fish and shellfish around the UK and Ireland that correlate with observed climate change. Cold-water species have declined in both abundance and geographical range, for example the Atlantic wolffish, most notably in the southern part of the North Sea.
- Large numbers of Atlantic bluefin tuna have been reported off the UK and Ireland since 2014 associated with warm marine conditions, and possibly climate driven changes in prey availability (e.g. Mackerel).
- Several species of cephalopods (especially squid) have shown noticeable increases in abundance and geographical spread in UK waters, a change consistent with warming waters. For many fish stocks assessed by fishery scientists, juvenile recruitment to the population during recent consecutive warm years in 2020 and in 2021 was low. The exceptions to this were some of the pelagic species (Atlantic mackerel, North Sea sprat, Irish Sea herring, blue whiting) and warm-water species (e.g. Western English Channel sole).
- Several studies have documented large episodic shocks to fisheries as a result of marine heatwaves and cold-spells. In the North Sea, catches of sole and seabass increased in years following cold-spells whereas catches of red mullet and edible crab decreased, impacts of heatwaves were less clear.

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What could happen in the future?

- Of all the species examined in a recent study, around half were predicted to benefit from more suitable habitat within the UK Exclusive Economic Zone (EEZ), including black seabream, seabass, sardine, red mullet, anchovy and pouting. Conversely, it is suggested that UK seas will become less suitable for species such as saithe, Atlantic wolffish, starry ray, halibut, ling, megrim and lemon sole.
- For the UK, it is estimated that direct potential losses due to reduced shellfish production associated with Ocean Acidification (OA), could range from 14% to 28% of fishery Net Present Value (NPV) by 2100.
- In a recent climate change risk assessment for 380 fishing fleets and 105 coastal regions in Europe, those in northern England and southern Scotland were identified as being particularly ‘at risk’, largely as a result of high stock sensitivity and low catch diversity.

INTRODUCTION

Commercial fishing remains one of the most important maritime activities in the United Kingdom (UK) and in Ireland. In 2021, UK fishing vessels landed 652,000 tonnes of fish and shellfish, accruing a revenue of around £921 million (MMO, 2022). In Ireland, domestic landings amounted to 218,600 tonnes with a value of €312 million (Perry *et al*., 2022). Nevertheless, there has been a recent contraction in the UK fishing industry, as a result of deliberate interventions to control fishing pressure and to ensure sustainable exploitation of European fish stocks. To some extent this contraction reflects the underlying influence of climatic factors on fish populations, which determine the level of fishing that can be sustained, given the prevailing environmental conditions. The UK industry now employs around 10,724 fishers, compared to 14,958 in 2001. There has been a similar decrease in the number of UK fishing vessels over this period – declining from 7,721 in 2001 to 5,783 in 2021. In Ireland the total number of fishing vessels is around 1,938 (in 2020) and this has remained relatively stable for the past decade, with 2,928 people directly engaged in the Irish fishing industry (Perry *et al*., 2022).

Recreational sea angling is a popular activity in the UK and Ireland that has both social and economic benefits, but can also impact on fish stocks. It has been estimated that 758,000 people participated in this activity in 2018 in the UK (participation rates were lower in 2019 due the social restrictions imposed during the COVID-19 pandemic). Catches amounted to around 46 million fish, 80% of which were released. Key target species include mackerel *Scomber scombrus*, whiting *Merlangius merlangus*, seabass *Dicentrarchus labrax*, cod *Gadus morhua* and pollack *Pollachius*

pollachius, although sharks and more recently bluefin tuna *Thunnus thynnus* are also important (Hyder *et al*., 2021).

The various impacts of climate change on *fisheries* in the UK were last reviewed as part of the MCCIP report card in 2020 (see Pinnegar *et al*., 2020) and also in the North Atlantic chapter of the FAO report *Impacts of Climate Change on Fisheries and Aquaculture* (see Peck and Pinnegar, 2018). However, an important development has been the emergence of a yearly 'watching brief' report produced by Seafish that aims to communicate new scientific evidence as well as industry observations of climate change impacts concerning wild-capture fisheries in the UK. This watching brief report has now been through four full iterations most recently in Spring 2022 (see www.seafish.org/article/climate-change-adaptation). Additionally, seafish have begun the process of updating their Adaptation Reporting Powers document on the 'wild-capture seafood industry', last produced in the winter of 2015/16 (Garrett *et al*. 2016). With regard to recreational fisheries, possible implications of climate change in the UK (but also elsewhere) were reviewed by Townhill *et al*. (2019).

The wild-capture seafood system can be impacted by climate change in many different ways, directly through damage to vessels and infrastructure or changes to working conditions, and indirectly though changes in the distribution and productivity of fish and shellfish. This review focusses on the consequences for fishery resources, fishing fleets and harbourside facilities, but does not consider the wider seafood supply chain (see Figure 1), or the logistics, processing, retail or consumers involved, nor the importation of fish and shellfish from elsewhere in the World. The latter are dealt with in the annual Seafish *Watching Brief* documents and will be covered in the revised *Seafish – Adaptation Reporting Powers* document on 'wild-capture seafood industry'.

As part of this 2023 MCCIP assessment, a separate supporting document has been prepared on climate change consequences for 'Fish' (see Fox *et al*., 2023). Clearly there is substantial overlap between the 'Fish' and 'Fisheries' supporting documents, but in general the 'Fisheries' document focusses on datasets derived from the commercial fishing industry or applies modelling to understand effects on fisheries and includes shellfish capture. By contrast, the 'Fish' document draws on fishery-independent survey datasets or experimental results; it considers fundamental aspects of fish biology, physiology and life history and it does not consider impacts on shellfish.

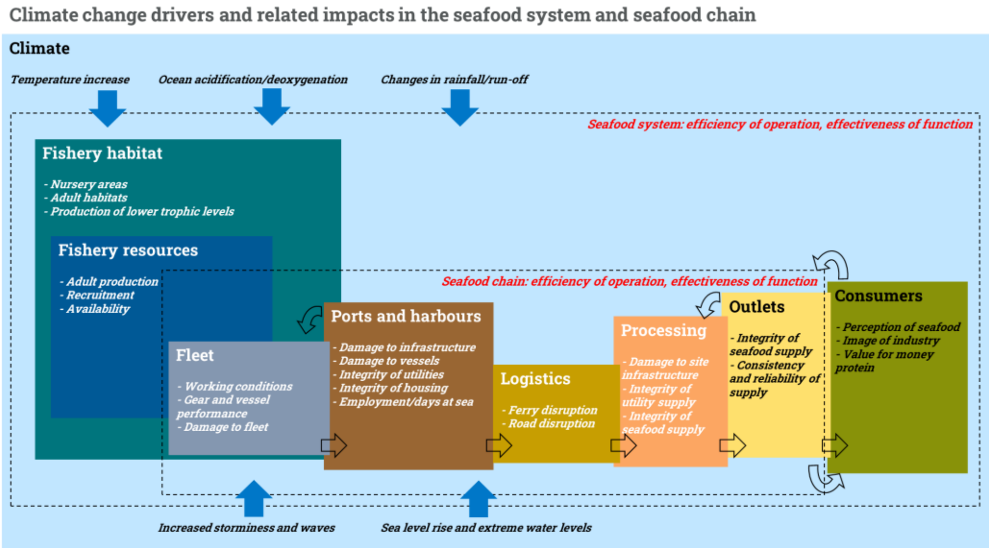


Figure 1: *Schematic diagram of the UK and Irish wild-capture fisheries system, illustrating the components that can be impacted either directly or indirectly by climate change.*

Developments in Legislation and Policy

On 23rd November 2020, the UK Fisheries Bill gained royal assent. The resulting Fisheries Act includes eight objectives, among these is Objective "h", concerning climate change. The "climate change objective" is that:

(a) adverse effect of fish and aquaculture activities on climate change is minimised, and
(b) fish and aquaculture activities adapt to climate change.

The Act itself does not set out the specifics of how these objectives will be achieved. Rather, it creates a legal requirement for the UK's four national fisheries authorities to produce a Joint Fisheries Statement (JFS) that does lay out a plan for how these objectives will be met. This Joint Fisheries Statement was released on 23 November 2022 and includes the following commitments:

> *"[4.2.14.9] The national fisheries authorities will continue working to understand and address the impacts of changing climatic conditions on marine species, habitats and fisheries, as highlighted by the Climate Change Committee's Climate Risk Independent Assessment (CCRA3), through mechanisms such as the Marine Climate Change Impacts Partnership. We will also ensure the findings are accessible to affected stakeholders and incorporated into our decision-making processes. Where relevant, we will use our international partnerships, including the International Alliance to Combat Ocean Acidification, to support that work."*

> *"[4.2.14.10] The fisheries policy authorities will work in partnership with the seafood sector to support their adaptation to the impacts of climate change and co-develop climate-adaptive management techniques to support sustainable fishing of stocks and aquaculture*

impacted by climate change, thereby contributing to meeting the climate change objective".

"[4.2.14.11] The fisheries policy authorities will seek to collaborate to take advantage of the opportunities and address the challenges which may arise from climate change, such as the developments for new capture fisheries or diversification of aquaculture."

In Ireland, fisheries are managed under the auspices of the EU Common Fisheries Policy. A 'Climate Change Sectoral Adaptation Plan' concerning 'Agriculture, Forest and Seafood' was published in November 2019 and this included actions to enhance climate change resilience in the fisheries sector (GOI, 2019).

What is already happening?

Effects on distribution

Observed shifts in the distribution of species have been the focus of many MCCIP report cards over the past 17 years. Recent studies have characterised shifts in the distribution of fish and shellfish around the UK and Ireland, and these have included observational studies based on fishery-independent scientific survey datasets (e.g. Mclean *et al*., 2019, 2021; Beukhof *et al*., 2019; Mérillet *et al*., 2020). In addition, studies using data from commercial fisheries have also demonstrated shifts in catch-per-unit-effort or bycatch patterns (e.g. Bluemel *et al*., 2021).

Mclean *et al*. (2021) examined fish distribution changes in both the North Pacific and North Atlantic (including seas around the British Isles) based on fishery-independent trawl survey data, by calculating the community temperature index (CTI), which tracks the mean thermal affinity of constituent fish species in the community. CTI is the weighted average (by catch composition) observed median temperature, across the species' current range. CTI closely tracked changes in sea surface temperature, increasing in 72% of locations, and notably 31% of these increases were primarily due to decreases in cold-affinity species. Increases in CTI occurred primarily along the north-east coast of the United States, in the seas around Scotland, the North Sea, the Baltic Sea, the Barents Sea, and around the Aleutian Islands. Tropicalization (increases in warm-affinity species) was stronger than deborealization (decreases in cold-affinity species) in the seas around Scotland and the North Sea.

Bluemel *et al*. (2021) examined long-term changes in the distribution and abundance of Atlantic wolffish *Anarhichas lupus* in the North Sea. *A. lupus* is a boreo-Arctic species that was once common across much of the central and northern North Sea but, since the 1980s, has declined in abundance and geographical range, with the shallower and more southerly parts of its range being the most impacted. Bycatch through fishing remains a serious threat and, considering the likely impacts of predicted climate change, threatens regional depletion and/or extirpation of this cold-water species.

A particular focus in recent years has been the apparent westward and north-westward spread of Atlantic mackerel *S. scombrus* into Icelandic and Faroese waters, with serious repercussions for fisheries quota allocation and governance. A review of these events and the transboundary negotiations that followed has been provided by Østhagen *et al*. (2022). Whether or not the shift was due to natural stock fluctuations or warming sea temperatures became a serious point of contention. During the period 2007–2016 the mackerel distribution range increased three-fold and the centre-of-gravity, based on an analysis of catch rates in relation to latitude and longitude, shifted westward by 1,650 km and northwards by 400 km (Olafsdottir *et al*., 2019). Distribution range peaked in 2014 and was positively correlated to Spawning Stock Biomass (SSB), i.e. density-dependent spreading out of the stock, but also associated with ambient seawater temperature and mesozooplankton density (Olafsdottir *et al*., 2019; ICES, 2020). The latest stock assessment for Atlantic mackerel (ICES, 2022a) suggests that the distribution area was stable at around 2.8–2.9 million km^2 during 2017–2019, however fishers have since witnessed a substantial eastward retreat in mackerel abundance during the summers of 2020–2021, when no mackerel were registered in Greenland waters, and a substantial decline was documented in Icelandic waters. The biomass of mackerel increased in the central and northern part of the Norwegian Sea, as well as the Barents Sea and Greenland Sea (ICES Subareas 1, 2, 5, 14) where catches increased significantly and amounted to 663,111 tonnes. Catches from Division 2.a (southern part of the Norwegian Sea) accounted for 61% of the total catch (ICES, 2022a). The total quantity of mackerel taken by Scottish vessels was 209,876 tonnes and 60,752 tonnes were taken by Irish vessels in 2021, mostly in western waters (ICES sub-areas 6,7 and 8) or the North Sea (ICES sub-area 4, and Division 3a) (ICES, 2022a).

Boyd *et al*. (2020) constructed an individual-based model (IBM) for Atlantic mackerel that incorporates spatial and temporal variation in food availability, temperature and exploitation, in order to simulate the consequences of management scenarios and/or future climate change. Results suggest that, over the range of scenarios considered, fishing mortality had a larger effect on the mackerel population than climate out to 2050. This result was evident in terms of stock size and spatial distribution in the summer months.

Some of the key ‘lessons learnt’ from the recent mackerel disputes are that changes in fish distribution due to climate change, and/or stock expansion, can jeopardize conservation objectives because fishers catch more than is allocated as quota. To avoid this issue, quotas, or catch shares, should be tailored to match the share of the fish stock biomass present within a country’s Exclusive Economic Zone, a concept known as ‘Zonal Attachment’. Fernandes and Fallon (2020) reviewed the ‘Zonal Attachment’ of transboundary fish stocks present in northern Europe, and in particular in the waters of the UK, the European Union, and Norway. The authors argue that with environmental change, and stock recovery under improved fisheries conservation, scientific evidence should be used not only to set absolute catch limits, but also to periodically re-examine catch shares (Fernandes and Fallon, 2020). In a global modelling study by Palacios-Abrantes *et al*. (2021) the authors estimated that by 2030, 23% of transboundary fish stocks will have shifted and 78% of the world's EEZs will have experienced at least one shifting stock. By 2030, global EEZs are projected to experience an average change of 59% in catch proportion of transboundary stocks. Many countries that are highly dependent on fisheries for livelihood and food security emerge as hotspots for transboundary shifts. These hotspots are characterized by early shifts in the distribution of an important number of transboundary stocks. Ireland was highlighted because shifting stocks account for less than 1% of fishing revenue in the country (compared to around 50% in the UK). However, for Ireland it is anticipated that catch proportion could change by as much as 25% by 2030 and 35% by 2060, as compared to less than 10% for the UK (Palacios-Abrantes *et al*., 2021; supplementary annex).

Recreational sea anglers are often the first to report unusual fish species occurring in British and Irish waters. Articles in angling magazines have increasingly included mentions of triggerfish (*Balistes capriscus*) around Ireland, Wales and south-west England, as well as other warm-water species characteristic of the Mediterranean, such as gilthead bream (*Sparus aurata*) off Salcombe and the Isle of Wight, and Comber (*Serranus cabrilla*) throughout the English Channel. Both commercial and recreational fishers have reported large numbers of Atlantic bluefin tuna *T. thynnus*, especially off Donegal and Cork in Ireland, and Devon and Cornwall in England. Horton *et al*. (2021) analysed a unique dataset assembled from a range of sources (including scientific surveys, ecotour records and bycatch data from the Irish albacore fishery) to demonstrate an increasing trend in effort-corrected tuna occurrence. Data suggest that sightings of bluefin tuna have increased markedly off the UK and Ireland since 2014. Historically this species had been present throughout much of the north-east Atlantic, where it had previously been the target of a UK sport fishery based in Yorkshire (Bennema, 2018).

Faillettaz *et al*. (2019) examined century-scale fluctuations in bluefin tuna abundance and distribution to demonstrate a strong influence of the Atlantic Multidecadal Oscillation (AMO). This study provides new insights into both the collapse of the Nordic bluefin tuna fishery circa 1963 and the recent resurgence in bluefin tuna abundance in the North-east Atlantic (especially around the British Isles). Spatial patterns of habitat suitability of bluefin tuna in the North Atlantic were assessed for positive (1929–1962; 1995 to present) and negative (1896–1928 and 1963–1994) AMO phases. This analysis showed that high records of bluefin tuna in the NE Atlantic coincided with high positive habitat suitability observed during positive (warm) AMO phases, while lower records occurred during negative (cool)

AMO phases when habitat suitability became negative. A similar finding was suggested by Horton *et al*. (2021) for the UK and Ireland specifically. However, Horton *et al*. (2021) showed that tuna did not re-appear in any considerable numbers off south-west England until 2014, nineteen years into the most recent warm AMO phase. Atlantic bluefin tuna migrate seasonally into higher latitude waters primarily to forage on caloric-rich pelagic prey such as mackerel, Atlantic saury *Scomberesox saurus*, sardine *Sardina pilchardus*, sprat *Sprattus sprattus*, herring *Clupea harengus* and anchovy *Engraulis encrasicolus*. Consequently, increases in the abundance of any of these species, either through range-expansion or population growth, could have a bottom-up effect on tuna residency (Horton *et al*. 2021).

Bluefin tuna stocks in the Atlantic are managed by the International Commission for the Conservation of Atlantic Tunas (ICCAT). The recent reappearance and re-distribution of bluefin tuna in large quantities off Norway and Iceland has prompted ICCAT to reconsider its criteria for allocating quota shares, such that these no longer only reflect 'track record', but they also consider the spatial distribution of species and the rights of coastal states to make use of resources present within their own EEZ, i.e. 'zonal attachment' (clause 7, in ICCAT 2015). During 2020–2022, scientific investigations into bluefin tuna migrations and movements have been conducted in the UK (in particular, tagging experiments) under the auspices of the Defra-funded THUNNUS UK and CHART programmes. In Ireland a similar catch-tag-release science-based fishery for recreational angling vessels has been in place since 2019.

Over the past 10 years, MCCIP have reported on increasing cephalopod (squid, cuttlefish and octopus) populations and on opportunities for the development of new fisheries around the UK and Ireland (for example in the Morray Firth). Oesterwind *et al*. (2022) recently provided a thorough overview of climate change-related modification of cephalopod biodiversity, abundance and distribution and in particular has documented changes in the cephalopod biodiversity of the North Sea at species level over the past 100 years. Some species, which seemed to migrate into the North Sea only for spawning or foraging in the nineteenth century, now occur permanently in the North Sea. This applies, for example, to *Loligo forbesii* and *Alloteuthis subulate* (and confirms earlier work by van der Kooij *et al*. 2016). The ommastrephids *Todaropsis eblanae* and *Illex coindetii*, are now constantly present in the North Sea, having previously been described only as accidental vagrants 100 years ago.

Doubleday *et al*. (2016) assembled global time–series data of cephalopod catch rates (catch per unit of fishing or sampling effort) and demonstrated that cephalopod populations have increased worldwide over the last six decades. Oesterwind *et al*. (2022) have shown that commercial catches of cephalopods have increased conspicuously in the North Sea from zero tonnes per year in the 1950s to more than 3000 tonnes per year in 2020. Veined squid *L. forbesii* and European squid *L. vulgaris* are the two main commercial squid species co-occurring on the northern shelf of the

European continent, yet little was known about reproduction within these species. Laptikhovsky *et al*. (2022) examined datasets from Britain, Germany, France and Ireland during the last 30 years, as well as from multinational Citizen Science projects, and found that seasonally, the position of the spawning grounds of both species is driven by the local temperature regime, although this is subject to considerable interannual variability. Future climate change could greatly impact the reproductive biology and distribution of these species, as has already been demonstrated for other squid species such as *I. coindetii.* Oesterwind *et al.* (2020) highlighted increased abundance of shortfin squid *I. coindetii* in the southern North Sea. Barrett *et al*. (2021) compared occurrences of lesser flying squid (*T. eblanae*) and *I. coindetii* with oceanographic data to gain insights into environmental predictors of spawning areas. Spawning *T. eblanae* were found in relatively cooler and more saline waters (6–8°C, 34.2–35.1 psu (Practical Salinity Units)) in the northern North Sea linked to the Fair Isle Current and East Shetland Atlantic Inflow, whereas spawning *I. coindetii* now occur across the entire North Sea (mostly at 9–10.5°C, 34.1–34.8 psu).

Effects on stock recruitment and fisheries yield

ICES defines ‘recruitment’ as *“The amount of fish added to the exploitable stock each year”* (ICES 2012). Mounting scientific evidence links the ‘recruitment’ of fish to prevailing climatic conditions, and in particular, sea surface temperature, the North Atlantic Oscillation (NAO) and the AMO.

Some fish species recruit into the fishery within the first year of life (e.g. sprat), whereas others (for example, North Sea saithe *Pollachius virens*), only enter the fishery as recruits after 3 or 4 years. Table 1 provides up-to-date recruitment estimates for commercial fish species of interest to UK and Irish fisheries, as derived from ICES stock assessments in 2022. For many (if not most) stocks and species, recruitment in 2020–2021 was low when compared to the long-term average (1980–2010). Exceptions to this include some pelagic species (e.g. North Sea sprat, North Atlantic blue whiting *Micromesistius poutassou*) that have benefited from successive strong year-classes entering the population in recent years. One widely-cited explanation for poor year classes is the ‘match-mismatch’ hypothesis of Cushing (1990), whereby reduced overlap in the timing of the spring or autumn zooplankton bloom and larval hatching dates can result in of larval starvation and hence reduced survival of recruits. Stronger recruitment of the certain warm-water species e.g. *Solea solea* (dover sole) was seen in more southerly areas, with strong recruitment in both 2020 and 2021 in the Bristol Channel/Celtic Sea and in 2020 only in the western English Channel and Irish Sea. Successive strong recruitment years were also seen for monkfish *Lophius piscatorius* in the Celtic Seas/Bay of Biscay region and plaice *Pleuronectes platessa* in the North Sea and the Eastern English Channel. Single years of stronger recruitment were observed for haddock *Melanogrammus aeglefinus* in the more northernly part of their range, specifically the North Sea and the North-east Arctic (in 2020) and Iceland (in 2021). A few other stocks exhibited strong recruitment in 2020 but not in 2021 (e.g. Norway pout *Trisopterus esmarkii* and whiting *M. merlangus* in the North Sea and herring *C. harengus* in the Irish Sea). For stocks experiencing continued poor recruitment (those indicated in red), it may be necessary for managers to be more precautionary in the future (see projection studies reported below), in order to ensure long-term resilience and persistence of these populations.

Table 1. Average stock recruitment for species of interest to commercial fisheries in the UK, compared to the reference period 1980-2010. Lower=red, Higher=blue. Age-at-recruitment will vary for each stock.

Species	**Stock**	**Average recruitment 1980–2010 (thousands)**	**2020 recruitment (thousands)**	**2021 recruitment (thousands)**
Cod (*Gadus morhua*)	North Sea, eastern English Channel, Skagerrak	660355	228230	132322
Cod (*Gadus morhua*)	Irish Sea	81052	9468	17562
Cod (*Gadus morhua*)	Eastern English Channel and southern Celtic Seas	10961	1305	923
Cod (*Gadus morhua*)	Norwegian Sea and Barents Sea (north of 67°N)	45123	42704	34086
Cod (*Gadus morhua*)	Iceland Grounds	145258	141829	129060
Cod (*Gadus morhua*)	West of Scotland	11283	2876	1974
Haddock (*Melanogrammus aeglefinus*)	North Sea, West of Scotland, Skagerrak	7440908	7955652	2499031
Haddock (*Melanogrammus aeglefinus*)	Irish Sea	418169	55310	286346
Haddock (*Melanogrammus aeglefinus*)	English Channel & Southern Celtic Seas	451034	186296	304566
Haddock (*Melanogrammus aeglefinus*)	Rockall*	76542	14947	50739
Haddock (*Melanogrammus aeglefinus*)	Iceland Grounds	80266	16548	148599
Haddock (*Melanogrammus aeglefinus*)	North-east Arctic (Barents Sea) *	264892	440809	158028
Mackerel (*Scomber scombrus*)	North-east Atlantic	3061518	2698510	6801162
Horse Mackerel (*Trachurus trachurus*)	North-east Atlantic	4684802	1165290	816224
Blue Whiting (*Micromesistius poutassou*)	North-east Atlantic and adjacent waters	18417247	26772174	71562826
Norway Pout (*Trisopterus esmarkii*)	North Sea, Skagerrak and Kattegat	46001703	61834000	25853000

Sandeel (*Ammodytes marinus*)	Central and southern North Sea, Dogger Bank (4.b–c, Sandeel Area 1r)	173628968	52904555	39626157
Sandeel (*Ammodytes marinus*)	Eastern Scotland (divisions 4.a–b, Sandeel Area 4)	106583031	62395268	46548252
Herring (*Clupea harengus*)	North Sea, Skagerrak and Kattegat, eastern English Channel	37141616	23368085	18346146
Herring (*Clupea harengus*)	Irish Sea (North of 52°30'N)	199600	593030	196418
Herring(*Clupea harengus*)	Irish Sea (South of 52°30'N) Celtic Sea, and southwest of Ireland	566086	108106	260375
Sprat (*Sprattus sprattus*)	Skagerrak, Kattegat and North Sea	85276545	85515000	69413200
Plaice (*Pleuronectes platessa*)	Irish Sea	20140	8749	9261
Plaice (*Pleuronectes platessa*)	North Sea & Skagerrak	3256396	4155293	3599960
Plaice (*Pleuronectes platessa*)	Eastern English Channel	67039	71614	163630
Turbot (*Scophthalmus maximus*)	North Sea	4438	4013	2197
Sole (*Solea solea*)	North Sea	164109	44846	43915
Sole (*Solea solea*)	Irish Sea	5682	7051	1405
Sole (*Solea solea*)	Bristol Channel, Celtic Sea	5668	6104	8071
Sole (*Solea solea*)	Eastern English Channel	25833	12386	14305
Sole (*Solea solea*)	Western English Channel	4492	9050	2745
Saithe (*Pollachius virens*)	North Sea, Rockall and West of Scotland, Skagerrak and Kattegat	148281	31416	49833
Whiting (*Merlangius merlangus*)	North Sea and eastern English Channel	17843058	21131946	14371814
Whiting (*Merlangius merlangus*)	Irish Sea	315556	107078	196382
Whiting (*Merlangius merlangus*)	West of Scotland	565133	199449	273676
Whiting (*Merlangius merlangus*)	Southern Celtic Seas and western English Channel	1169524	494034	353025
Megrim (*Lepidorhombus whiffiagonis*)	West and southwest of Ireland, Bay of Biscay	234437	182574	159912
Monkfish (*Lophius piscatorius*)	Celtic Seas, Bay of Biscay	112770	485415	146922

*Values for these stocks are from the 2021 assessment, as the recruitment of these stocks was not provided in the 2022 ICES advice process.

**Where time series were not available for the entire period 1980–2010 averages are based on the limited number of available years prior to 2010.

Bentley *et al*. (2020) identified correlations between large-scale climatic indicators (such as AMO and NAO), seawater temperature, primary and secondary productivity, with fish recruitment in the Irish Sea. Model simulations suggested that historic environmental change has suppressed the overall production of commercial finfish in recent years, limiting opportunities for the fishing industry, whilst also dampening the rate of stock recovery, despite marked reductions in fishing effort.

In Europe, marine fish stocks are mostly managed through assessment of their exploitation and ecological status compared to reference points such as Maximum Sustainable Yield (MSY). Free *et al*. (2019) used temperature-dependent population models to measure the influence of warming on the productivity of 235 populations of commercial marine fish in 38 ecoregions. Some populations responded positively (nine populations) and others responded negatively (19 populations) to warming. Hindcasts indicate that the MSY of the evaluated populations decreased by 4.1% from 1930 to 2010, with five ecoregions experiencing losses of 15 to 35%. Notably, populations in the North Sea and Celtic–Biscay shelf (i.e. around the British Isles) were among the most negatively impacted. The authors found that exploitation history and temperature change interacted to determine the vulnerability of populations to warming. Populations that had experienced intense and prolonged overfishing were more likely to be negatively influenced by warming, especially where they had also experienced rapid warming (>0.2°C per decade).

The integration of climate conditions into fisheries management is a key challenge which requires both understanding of fish populations, and a pragmatic approach to implementation within the current advice framework (Howell *et al*., 2021). Recent research focused on the Irish Sea has demonstrated the potential for incorporating ecosystem indicators (such as sea temperature or zooplankton abundance) into the current framework for ICES single-stock advice. This method involves two key stages; (a) the derivation of key ecosystem indicators linked to the productivity of fish species in a multispecies/ecosystem model, and (b) the use of these ecosystem indicators to provide a management option in the single-stock advice. Specifically, the status of the indicator (e.g. sea surface temperature) relative to its long-term range, is used to scale the fishing advice within the F_{MSY} range of the stock, such that advised fishing pressure increases when the ecosystem is in a positive state for the stock and decreases when ecosystem conditions are poor. Retrospective ecosystem modelling of Irish Sea cod, herring, *Nephrops* and whiting stocks suggests that higher stability and long-term yields could be achieved through this adjustment of F_{MSY} i.e. the fishing pressure that gives the maximum sustainable yield in the long term (Bentley *et al*., 2021) to prevailing climatic conditions. This method (termed F_{ECO}) has been incorporated into the ICES advice scenarios for Irish Sea cod for the first time in 2022 (ICES, 2022b). This method provides a pragmatic step towards Ecosystem Based Fisheries Management, however, it does not yet capture the full complexity of the ecosystem which could only be achieved through the integration of multi-species models in future (e.g. Thorpe and De Oliveira, 2019, Spence *et al*., 2021).

Heat waves, cold snaps and die-offs

A number of studies have documented large episodic shocks to fisheries as a result of marine temperature extremes. These extreme events occur when ocean temperature is exceptionally high or low relative to the climatological average of the area and can last for days, months, or even a few years. Wakelin *et al*. (2021) provided the first study to identify a link between extreme temperature events and landings of key fish and shellfish stocks in the North Sea. The authors used daily near-bottom seawater temperature data spanning the period 1993–2019. Following Hobday *et al*. (2016), marine heatwaves were identified as periods of at least five consecutive days when the temperature exceeded the threshold of the 90th percentile of observations at a particular locality. By analogy, marine cold-spells were defined to be periods of five or more days when the temperature was lower than the 10th percentile. For the southern North Sea, widespread anomalous heatwaves and cold-spells occurred throughout the period 1993–2019 but with no significant trends in the extent or magnitude of events. Winter cold-spells occurred in 1994, 1996, 1997, 2010, 2011, 2013 and 2018. There were widespread heatwaves in 1998, 2002, 2003, 2006, 2007 and all years between 2014–2019 (Wakelin *et al*., 2021). Landings of sole and seabass increased in years with cold-spells, while landings of red mullet and edible crabs decreased. For heatwaves, the impact on fisheries catch lagged the temperature event by five years: sole, European lobster and seabass landings all increased, though these weak statistical associations could be spurious (Wakelin *et al*., 2021).

The extent to which marine heatwaves have negative impacts on fish biomass or community composition has also been questioned by Fredston et al. (2023). These authors investigated the effects of 248 sea-bed heatwaves from 1993 to 2019 on marine fishes by analysing 82,322 hauls (samples) from scientific surveys of continental shelf ecosystems in North America and Europe. The effects of marine heatwaves on fish biomass were often minimal and could not be distinguished from natural and sampling variability, including those occurring in the North Sea (also see commentary by Payne 2023).

During February 2018, dying starfish, crab, mussel and lobsters were reported on the North Sea coast of England following a sudden 3°C drop in seawater temperature between 26th February and 4th March (Pinnegar *et al*., 2020). Previous cold-spell events such as the ‘big freeze’ in 1963 witnessed similar large-scale fish die-offs, especially of warm-water species such as sole (Woodhead, 1964; Hurst ,2007).

Extreme weather and impacts on fishery operations

Changing storminess poses a direct risk to fisheries. Storms disrupt fishing effort and pose a physical danger to fishers, their vessels and gear, as well as causing damage to onshore infrastructure and hardship in fishing communities. Ocean warming may have significant impacts on fish catches over the next 30 to 50 years, but changing storminess has the potential to cause more immediate and catastrophic impacts (Sainsbury *et al*., 2018).

Uncertainty in projections of past and future storminess from global and regional climate models remains high as a result of widespread variation in analytical methods, poor historical observational data, and the challenge of distinguishing climate change from natural climate variability. At present, confidence in the wind and storm projections from Global Climate Models (GCMs) and downscaled Regional Climate Models (RCMs) is relatively low (see Bricheno *et al*., 2023). However, models tend to suggest that north-west Europe will experience fewer storms overall in the future, though these will be more intense (Mölter *et al*., 2016; Outten and Sobolowski, 2021), i.e. high wind speeds and wave heights.

The trade-off between physical risk at sea and the anticipated economic rewards of continued fishing under adverse weather conditions is a critical component of fishers' trip decisions but is poorly understood. Sainsbury *et al* (2021) employed a stated choice experiment with skippers from south-west England (Padstow, Newquay, Hayle, Newlyn, Cadgwith, Mevagissey and Looe) to empirically assess how fishers trade off the risks from greater wind speed and wave height with the benefits of expected catch and prices. Fishers preferred increased wind speed and wave height up to a threshold, after which they became increasingly averse to worsening conditions and opted to cease operations. However, fishing gear, vessel length, presence of crew, vessel ownership, recent fishing success and reliance on fishing income can all influence the skippers' decisions about whether or not to go to sea (Sainsbury *et al*., 2021). Pfeiffer (2020) offered further insights from a study conducted in the United States. This study demonstrated that fishers' aversion to storms decreases with increasing vessel size and increases with the severity of the storm warning, although individual fishers' risk preferences may differ. More-experienced captains may be less averse to certain types of storms because they have experience-based confidence in their ability to safely navigate their vessel through particular conditions. On the other hand, fishing business practices, such as quota leasing or delivery contracts with processors, may reduce a fisher's ability to adjust trip timing and to minimize risk.

Watson *et al*. (2022) studied fisher decisions about when, or when not, to leave port, using the under 10-metre fleet targeting seabass in the UK (in the ports of Plymouth, Burry Port, West Mersea and Weymouth) as a case study. This study showed that fewer under 10-metre fishing vessels left port to go fishing with increasing wave height and that fishing success was lower when wave height was greater. Due to their small size, the vessels that make up the under 10-metre fleet are especially vulnerable to rough weather. The port with the smallest mean vessel size was Burry Port (south Wales) and this was the port seemingly most impacted by wave height (Watson *et al*., 2022).

Fishing remains the most dangerous occupation in the UK. The fatal accident rate is 115 times higher than that in the general workforce and much of this is related to operating in poor weather conditions (Roberts *et al*., 2010). In 2021, ten commercial fishers lost their lives at sea in accidents, making it the highest number of deaths in a decade, according to the Marine Accident Investigation Branch (MAIB). This compares to two deaths in 2020 and is double the yearly average over the past five years. There has been very little recent research with regard to predicting future accidents and casualties in the UK and Ireland. However, Rezaee *et al*. (2016a,b,c) proposed a general framework (applied to NW Canada) to quantify fishing incident risks due to anticipated long-term changes in weather conditions elsewhere. This framework established relationships between observed (1980–1999) fishing safety incidents and weather conditions and then predicted future risks (2081–2099) according to these relationships with respect to projected changes in weather patterns. For Atlantic Canada, the authors concluded that the environmental conditions that drive fishing incidents are expected to remain very similar to the end of this century. Whether this would also be the case for the UK and Ireland remains unclear (Rezaee *et al*., 2016a).

Becker *et al*. (2018) provided an international review of knowledge concerning climate risks, and adaptation responses, for ports and their supply chains. Evidence from both academic and grey literature indicates that there has already been major damage and disruption to ports across the world from climate-related hazards and that such impacts are projected to increase in the years and decades to come (Becker *et al*. 2018). One of the most powerful and damaging storms in the UK this decade, Storm Arwen occurred in November 2021 and led to the sinking of fishing vessels in harbours at Amble, Northumberland and Lossiemouth, Scotland.

Associated British Ports (ABP) own and operate 21 harbours around the country, including many that are of importance to the UK fishing industry. According to their most recent Adaptation Reporting Powers assessment (ABP, 2021), the most serious climate change threats are: (1) flood damage of harbour authority assets, and (2) interruption to port operations during storm events.

Sea-level rise will increase the likelihood of flood damage to harbour authority assets. This could include damage to infrastructure, including electricity supply and loss of operation with potential knock-on effects to other critical infrastructure. The potential for increased storminess could also result in damage to harbour authority assets resulting in increased survey and maintenance costs as well as reduction or temporary interruption of operations (to maintain safety of pilots and port staff). All other climate change risks were assessed as ‘low’ (ABP, 2021).

In late 2021, Franco (2023) asked UK seafood business to assess the occurrence, severity, and detectability of a range of risks to their operations, including how likely their business was to anticipate, to be affected by, lose, or gain from changes to climate including indirect effects and extreme weather events. Over 92% of respondents considered it was somewhat likely to very likely that they would be affected by changes to climate. The vast majority answered that they were likely to lose and unlikely to gain from these changes. 83% considered it was somewhat likely to very likely that they would lose from these changes, and 88% considered that it was somewhat unlikely to very unlikely that they would win from these changes. However, businesses were split on how likely they considered they could anticipate these changes: 29% considered it unlikely that their business could anticipate these changes, whilst 38% considered it likely.

What could happen in the future?

Future distribution changes

In recent years there has been a proliferation of studies aiming to determine future distributions of commercial fish and shellfish and this includes many studies of relevance to the UK and Ireland. Some of these studies were initiated in anticipation of transboundary quota disputes that might arise as a result of the UK departing the European Union and hence a need to assess 'zonal attachment'. Others were instigated in recognition that changes are already underway and that fishers are having to adapt to substantial shifts in catches compared to a few years ago.

Townhill *et al*. (2023) provided future projections of distribution and habitat suitability for 49 fish and shellfish species of commercial importance in the UK and Ireland (see Figure 2). Using an ensemble of five species distribution models and three different climate change scenarios, with a focus on the north-west European shelf, this study quantified habitat suitability and latitudinal shifts in the recent past (1997–2016) and in two future periods (2030–2050 and 2050–2070). Around half of the species were predicted to have consistently more suitable habitat in the future within the UK EEZ, including black seabream *Spondyliosoma cantharus*, seabass, sardine, surmullet (red mullet) *Mullus surmuletus*, anchovy and pouting (bib) *Trisopterus luscus*. Conversely, results indicated significant decline in suitability for other species including saithe, Atlantic wolffish, starry ray *Amblyraja radiata*, halibut *Hippoglossus hippoglossus*, ling *Molva molva*, megrim *Lepidorhombus whiffiagonis* and lemon sole *Microstomus kitt*. While there are differences in the magnitude of change, and models performed better for some species compared with others, overall the general trends in habitat suitability and abundance were robust across models, and climate scenarios (Townhill *et al*., 2023).

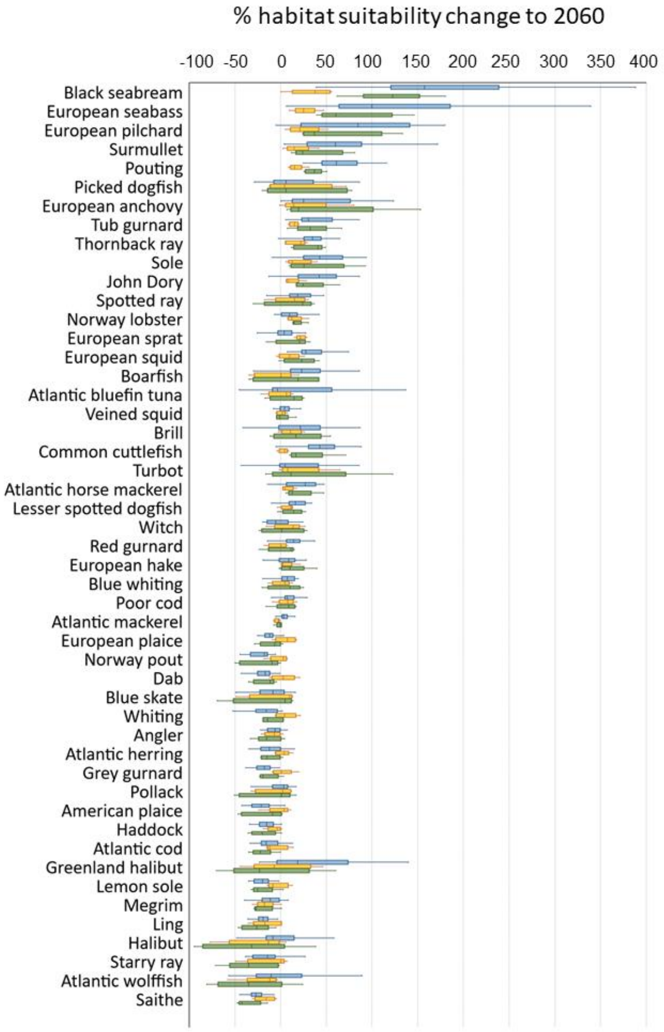


Figure 2: *The percentage change in suitable habitat in the UK EEZ by 2060 under the different climate change scenarios. Blue = SRES A1B ensemble mean. Orange = RCP4.5. Green = RCP8.5. A positive habitat suitability change indicates that the area will become more suitable in the future for the species. A negative habitat suitability change shows that the habitat is less suitable for that species in the future (from Townhill* et al., 2023).

Schickele *et al*. (2021) investigated potential changes in the spatial distribution of seven small pelagic fish species in Europe under several climate change scenarios over the 21st century. Under all scenarios, results revealed that the environmental suitability for Atlantic horse mackerel *Trachurus trachurus* and sprat may decrease around the British Isles, but suitability for sardine, anchovy, Mediterranean horse mackerel *Trachurus mediteraneus* and bogue *Boops boops* may increase, especially in the North Sea. Schickele *et al*. (2021) used a similar method to provide future distribution projections for three commercially important cephalopods (*Octopus vulgaris*, *Sepia officinalis* and *Loligo vulgaris*), and suggested that environmental suitability will increase rapidly in the North, Norwegian and Baltic Seas for all three species.

Fernandes *et al*. (2020b) used a 26-year time-series study of fish surveys with high spatial resolution in the North-east Atlantic to assess the ability of models to correctly simulate past changes in fish distribution and abundance in response to climate. Discrepancies between fishery model runs decreased dramatically when results were aggregated to larger scales (e.g. the whole North Sea), to total catches rather than individual species or when the ensemble mean was used instead of individual climate simulations. The conclusion of this work is that, while models can help guide fisheries management at larger spatial scales, caution is needed at smaller scales (Fernandes *et al*., 2020b).

Future fisheries yield

Previous MCCIP reports (e.g. Pinnegar *et al*., 2020) have noted that efforts to provide projections of future fisheries yields have been heavily constrained by information available from downscaled biogeochemical models (i.e. those that include plankton dynamics as well as physical variables such as temperature and salinity), and in particular assumptions concerning the future trajectory of primary production around the UK and Ireland. Some modelling studies have assumed that primary production (plankton productivity) will increase as a result of long-term climate change, whereas most studies have assumed that primary production will decline in the future, resulting in contradictory expectations for fishery yield. Understanding how climate change will impact the base of the marine food-web will be fundamental to determining consequences for fisheries (Spence *et al*., 2022) but modelling short-term inter-annual dynamics of primary production remains very challenging (Spence *et al*., 2022).

Travers-Trolet *et al*. (2020) explored climate change impacts on MSY reference points using a multi-species model applied to the Eastern English Channel and assuming two contrasting climate-change scenarios (RCP 4.5 and RCP 8.5). In this study primary and secondary production were decreased slightly, growth parameters were modified, reproduction phenology was advanced, and spatial distribution was impacted for species at their southern boundaries of distribution. For 80% of cases, F_{MSY} projections showed a consistent decreasing pattern in the future under both climate change scenarios, inferring the need to reassess exploitation levels to ensure that marine stocks remain healthy and persist in the long-term.

Fernandes *et al*. (2020a) explored the potential impact of different climate change scenarios on the MSY (Maximum Sustainable Yield) of four commercial pelagic species in the North-East Atlantic: Atlantic mackerel, sprat, herring and blue whiting (*Micromesistius poutassou*). MSY for herring and blue whiting increased under the RCP2.6 scenario, but future projections under RCP8.5 showed mixed responses with either decreases or no changes forecasted. Overall, increases in potential catch were projected in the Norwegian Sea, and decreases were projected in the Celtic Sea. These changes in catch were mainly driven by changes in temperature and primary production, which the authors assumed will increase in areas II and III (Norwegian Sea and Skagerrak) but will decrease everywhere else, including the North Sea, Iceland, west of Scotland and Celtic Sea (areas IV, V, VI and VII respectively; Fernandes *et al*., 2020a).

Ocean Acidification

After a surge in research activity in the mid 2010s focussing on the impact of ocean acidification (OA), there has been a general lack of locally-relevant studies or even monitoring of ocean pH around much of the UK and Ireland in recent years (Findlay *et al*., 2022; Ostle *et al*., 2016).

Mangi *et al*. (2018) reviewed laboratory experiments on commercial shellfish species, focusing on crustaceans and molluscs of interest to the UK and Ireland, and taking account of realistic pH scenarios for the next 80 years. This study showed that direct losses due to reduced shellfish production could range from 14% to 28% of fishery net present value by 2100. This equates to annual economic losses of between £3 and £6 billion of the UK's GDP at 2013 levels, under a medium- and high-emission scenario. The study also highlighted regional variations between the UK devolved nations, due to different shellfish production practices, and to varying sensitivities of the species harvested. Overall, Wales was suggested to be the most heavily impacted nation, with losses of mollusc fisheries projected at 30–59% of net present value. Predicted losses for England were 16–33%, for Scotland 10–21% and for Northern Ireland 16–32%, largely because wild-capture fisheries and aquaculture are more reliant on crustaceans (especially *Nephrops norvegicus*) in these nations, which are known to be more robust to ocean acidification compared molluscs (Styf *et al*., 2013).

Responses to OA in finfish are particularly uncertain, although several recent studies have noted that early life stages (eggs and young fish larvae) may be more sensitive to the direct effect of OA than adults. Larval survival and recruitment of the cod were found to be heavily impaired by end-of-century levels of OA (Stiasny *et al*., 2016), however significant interactions were detected between acidification, parental exposure and food availability (Stiasny *et al*., 2018, 2019). Larvae fed to capacity showed little difference in growth due to the CO_2 treatment. Larvae under energy limitation (starvation) were significantly larger and had overly-developed skeletal structures in the elevated CO_2 treatment compared to the ambient CO_2 treatment (Stiasny *et al*., 2019). While direct effects of OA on finfish around the UK and Northern Europe are not monitored, some theoretical studies have used available experimental data to explore the potential effects on cod stocks and fisheries. If recruitment is depressed to the extent suggested in experiments (e.g. Stiasny *et al*., 2016, 2017, 2018), then even relatively healthy stocks such as the North-east Arctic cod (*G. morhua*) would in the long-term face a serious risk of collapse (Königstein *et al*., 2018, Hänsel *et al*., 2020). For the Western Baltic cod stock, which is already close to its thermal limits, is under intense fishing pressure and is exposed to many other anthropogenic impacts, the negative added effects of ocean acidification could be very problematic (Voss *et al*., 2019).

A recent paper by Fields *et al*. (2022) suggests that, against expectations, elevated pCO_2/lower pH in future oceans may be beneficial to the copepod *Calanus finmarchicus*. *C. finmarchicus* are an important lipid-rich, prey resource for many fish larvae, including cod, haddock and sandeel as well as adult mackerel, herring and blue whiting. Experiments have been performed on different taxa, life stages, and at different pH levels. A recent meta-analysis of 985 studies, demonstrated that echinoderms, cephalopods, and crustaceans are on the whole capable of tolerating conditions expected in the future (a pH of ~7.1 by the 2100s), whereas bivalve molluscs, calcifying algae and corals are more sensitive to these pH changes (Leung *et al*., 2022). Despite this wealth of information, several key challenges remain, including: (1) uncertainty about how to incorporate current pH ranges and natural variability actually experienced by organisms into experiments, and (2) how to bring this information together to support analysis and assessments at the broader ecosystem level.

Townhill *et al*. (2022) considered the UK commercial shellfish fishery as a case study to demonstrate how different types of scientific research (e.g. experimental research, spatial monitoring and modelling) can be successfully combined to assess the consequences of OA. Findings indicate that that in most cases the lowest pH values used in experiments are not projected to be experienced in the UK waters even by the end of this century. Indeed, at the pH minima observed in the model outputs for end-of-century, the experiments generally show no effect. Under the RCP8.5 scenario, the regional model of the north-western European shelf projects that the climatological pH range of bottom water pH rarely goes to <7.6, a value of pH that experimental evidence suggests most of the species seem able to withstand, however sub-lethal impacts have been recorded and the implications of these for wild populations are not yet understood (e.g. lowered immune response in Norway lobster *Nephrops norvegicus*, reduction in size in blue mussels *Mytilus edulis* and common cockle *Cerastoderma edule*). The notable geographical exceptions are the Norwegian Trench, where surface waters are anticipated to experience a pH decline to <7.6, and also a small patch of the Celtic Sea south of Ireland, where bottom waters are anticipated to decline to <7.6. This latter area is important for the Celtic Sea Norway lobster (*N. norvegicus*) fishery. On first analysis therefore, it would seem that impacts on commercially exploited shellfish in UK waters will be rather limited (Townhill *et al*., 2022). Much of the north-western European shelf will, however, experience novel (i.e. not previously witnessed, within the last 1000 or so years) pH by the end of the century, especially in bottom waters (Townhill *et al*., 2022). This suggests that even if shellfish are not projected to experience pH levels beyond the critical thresholds highlighted by experimental work, they will most likely be exposed to a pH level never witnessed in the past.

In the North Sea, pH levels vary considerably each year due to seasonal and interannual variability as well as spatially (Provoost *et al*., 2010), and past measurements show that between 1984 and 2014 this variation was quite large, with extreme local values of ~6.5 to 9.3 in the top 20m of the water column (Provoost *et al*., 2010; Ostle *et al*., 2016). The seasonal and interannual variability in the North Sea is commonly of the order of 0.3 pH units (Ostle *et al*., 2016). Individuals of the same species from a more variable environment (such as inshore coastal waters) may be pre-adapted to withstand temporarily low pH conditions compared to individuals of the same species obtained from a more stable offshore location (Townhill *et al*., 2022).

Climate risk assessment of UK and EU fisheries

A new climate change risk assessment (Payne *et al*., 2021) has attempted to rank European fisheries and fishery-dependent coastal communities in terms of the threat posed by future climate change. This study combined biological traits with physiological metrics to differentiate climate sensitivities of 556 populations of fish (Payne *et al*., 2021). Scores for Hazard, Exposure and Vulnerability were combined to assess the relative climate 'Risk' to 380 fishing fleets and 105 coastal regions in Europe. Hazard metrics were based on catch composition of fisheries and the perceived stock sensitivity to climate change, Exposure metrics were based on catch diversity or dominance and Vulnerability metrics were based on the on the gross-domestic product per capita of the region or the net profit margin of the individual fleet (Payne *et al*. 2021).

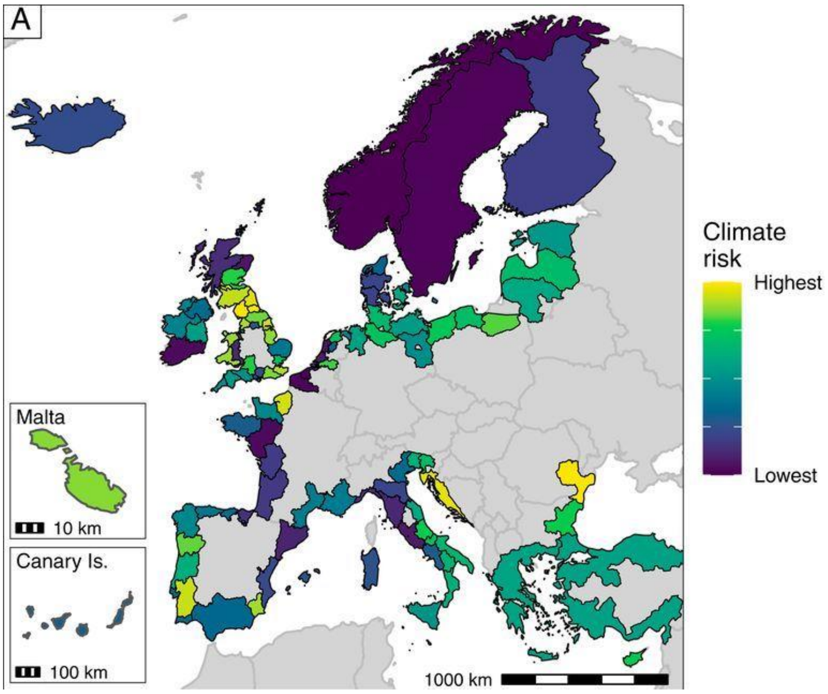


Figure 3: *The combined climate risk ranking to fisheries for each coastal region of Europe (from Payne* et al.*, 2021).*

Countries in south-east Europe as well as the UK were identified as having the highest risks to both fishing fleets and coastal regions overall, but often for very contrasting reasons (Payne *et al*., 2021). The UK was highlighted primarily because of high hazard scores (stock sensitivity, as weighted by catch composition) combined with high exposure scores (low catch diversity) compared to other countries. Ireland received moderate risk scores for both fleets and coastal regions. The analysis also revealed appreciable variation in the climate risk within the European continent and even within a single country (Figure 3). In the UK, for example, climate risk was greatest in the north of England, while fisheries in northern Scotland and the south of England exhibited much lower risk. Indeed, six of the ten regions with the highest climate risk in Europe, including the overall top region (Tees Valley and Durham), were in the UK. These results were strongly influenced by high-hazard scores for the species landed in these regions combined with high exposure (low catch diversity) and high vulnerability due to relatively low GDP per capita in some of these regions (Payne *et al*., 2021).

Statistical Regions of the UK where fisheries exhibit the highest climate change risk score:

- Tees Valley and Durham
- Cumbria
- West Central Scotland
- Northumberland/ Tyne and Wear
- East Yorkshire and Northern Lincolnshire
- Southern Scotland.

Statistical Regions of the UK where fisheries exhibit the lowest climate change risk score:

- North Eastern Scotland
- East Wales
- Highlands and Islands
- Hampshire and Isle of Wight.

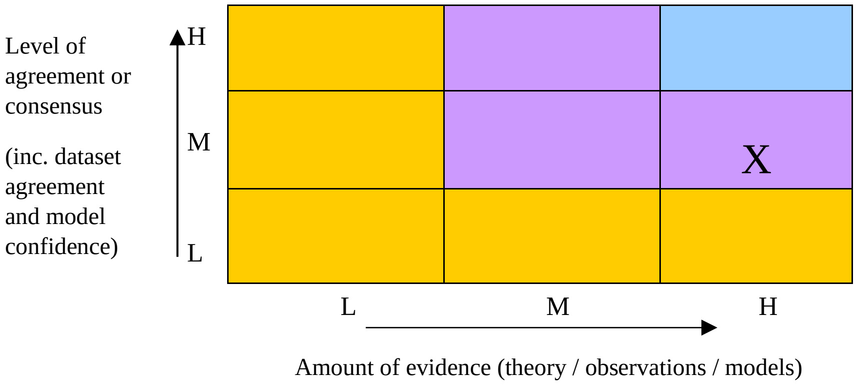
In Ireland, the highest risk score was assigned to the 'Eastern and Midland' region (see Figure 3), largely as a result of high-hazard scores and climate sensitivity of the species landed. However, risk scores were still much lower compared to many of those in the UK. The lowest climate change risk score in Ireland was assigned to the ‘Southern’ region, where climate change risks were identified as being among the lowest in Europe (ranked 100th out of 105).

Systematic differences in climate risk were also seen among gear types, in which dredgers had the highest climate risk (Payne *et al*., 2021). These fleets generally targeted populations with high climate hazards and had low species diversity in their catches (giving high exposure); good profitability, on the other hand, lowered their vulnerability and somewhat reduced overall risk. Fleets using pelagic and demersal trawls together with purse seine fleets had the lowest climate risks, primarily due to the low hazard scores associated with the target species on which they focus (Payne *et al*., 2021).

This analysis (by Payne *et al*., 2021) highlights the wide variety of challenges facing European fisheries in adapting to a changing climate. In some cases, a focus on building adaptive capacity in coastal regions would be of most benefit (e.g., by creating alternative employment opportunities or providing an economic ‘safety net’ through wider social measures). In other regions, fleet risks dominate, and therefore, increasing the efficiency, adaptive capacity, and catch diversity of the fleets would appear to be a priority. Some areas, such as northern England both types of intervention are required and therefore these regions and fleets present the greatest adaptation challenges (Payne *et al*., 2021).

CONFIDENCE ASSESSMENT

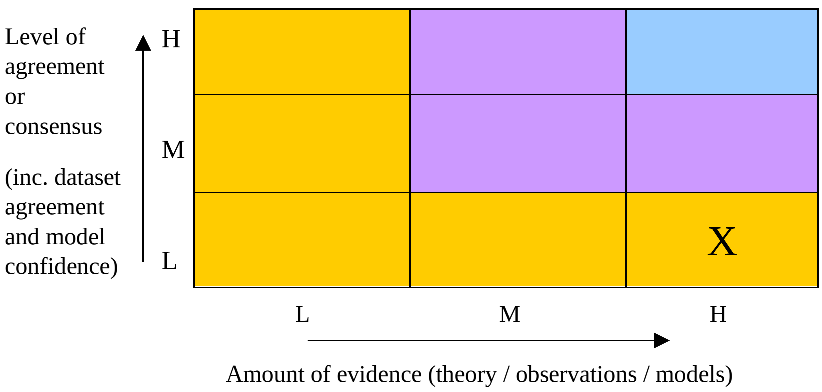
What is already happening?



Since the last MCCIP assessment in 2020 (Pinnegar *et al*., 2020), many more studies have been published on the changing distribution of species or climate impacts on recruitment patterns and so forth, but there remains limited information on heat waves and storminess. Some of the information available is annecdotal in nature or is difficult to 'attribute' to climate change with any certainty. In addition, while there is abundant information on observed biological impacts (see the MCCIP report on 'fish', by Fox *et al*., 2023), there is much less on consequences for fleets and fishing communities. That being said, much can be learnt from a recent UKRI sponsored exploration of seafood industry resilience in the light of the COVID-19 pandemic (Franco, 2023). This involved data collection through structured interviews and surveys; modelling of the industry supply network to explore systemic and unintended consequences for resilience; and in-depth case studies to investigate business model adaptation (Franco, 2023).

'Fisheries research' remains one of the most active fields in marine science, with a huge body of existing work over the past 100 years, and new papers appearing all the time. Hence, the amount of available evidence is judged as being 'high', but the level of agreement and consensus is still judged as being 'medium'. Consequently, the overall assessment has not changed from the 2020 MCCIP Report Card.

What could happen in the future?



The number of projection studies of relevance to the UK and Ireland has gone up dramatically in recent years, hence the shift to the right in the confidence matrix above, recognising an increase in the 'amount of evidence'. Furthermore, many projection studies now make use of 'ensembles' of subtly different biological models in order to better characterise uncertainty, when this was not often the case in the past. However, there are still considerable uncertainties and disagreements about the trajectory of primary productivity and this has knock-on impacts for fisheries yield projections in particular. Similarly, there are still some contradictions in the ocean acidification literature, with some projections suggesting considerable economic losses (e.g. Mangi *et al*., 2018) and others suggesting negligible impacts (e.g. Townhill *et al*., 2022) in the future.

KEY CHALLENGES AND EMERGING ISSUES

- As species continue to shift their distributions, the need for 'adaptive' transboundary quota allocations or 'quota swaps' will remain a key challenge. In addition, trans-boundary trading of fish and shellfish could be problematic following the exit of the UK from the EU. At the moment most of the fish consumed within the UK (e.g. cod and haddock) are imported from northerly countries such as Iceland and Norway, whereas most of the fish or shellfish caught in the UK are exported to countries farther south (see Harrison *et al*., 2023), where consumers have a tradition of eating these species. This can be viewed as 'climate maladaptation'.
- More work is needed on deriving effective climate change adaptation measures for fisheries. Elsewhere in the world, a wide diversity of interventions have been tried or advocated (see Poulain *et al*., 2018), while in the UK and Ireland, comparable discussions are only just beginning. The UK Seafood Fund: Fisheries Industry Science Partnerships (FISP) scheme does include climate change as one of its core themes, but so far very few projects have focussed on this issue.
- Increasing attention is being given to the role that fisheries play in generating carbon emissions and how to achieve 'net zero' emissions by the year 2050 (i.e. climate change 'mitigation' rather than impacts or adaptation). Added to this, greater focus is being placed on the resuspension of buried carbon by trawling activity, and whether restrictions of fishing activity in marine protected areas could have benefits for climate change mitigation.
- Inadequate or contradictory projections of future storminess and of future primary productivity, make assessments of consequences for commercial fisheries very difficult.

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