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Impacts of climate change on fisheries

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EXECUTIVE SUMMARY

What is already happening?

Both commercial and recreational fishermen have responded to new opportunities in recent years, as warm-water species have moved in and their exploitation has become viable for the first time. Examples include boarfish, triggerfish, squid and seabass.

Boarfish landings from the Celtic Sea have grown rapidly from less than 120 t in 2001, to more than 139 000 t in 2010. Ireland has successfully negotiated for ⅔ of the EU boarfish quota.

Strong relationships have been found to exist between 'year-class strength' (the number of juvenile fish) and various climatic indices.

The timing of spawning in sole has shifted earlier at a rate of 1.5 weeks per decade since 1970.

What could happen?

Considerable progress has been made since 2010/11 with regard to making future projections for both fish and fisheries. These advancements have followed the application of complex ecosystem or fish distribution models.

By the 2090s horse mackerel and anchovy are expected to show increased probability of occurrence in northern British waters, pollack, haddock, and saithe will show a decrease in southern waters.

Ocean acidification may have direct and indirect impacts on the recruitment, growth and survival of exploited species. However, there is little consensus about implications for commercial fisheries. Opinions range from wholesale degradation of marine ecosystems to negligible impacts with minimal economic consequences.

FULL REVIEW

Commercial fishing is an important economic activity in coastal regions of the UK and in the Republic of Ireland. In 2011, total landings of fish and shellfish were 599,600 tonnes into the UK and 198,937 tonnes into Ireland, with a first-sale value of £828.2 million and €269 million respectively (MMO 2011; SFPA, 2011). Overall, the UK fishing fleet (including those in the Isle of Man and Channel Islands) consists of ~6477 vessels, directly employing 12,703 people, while the processing sector employs an additional ~18,000 people. The Irish fishing fleet consists of ~1700 registered vessels, the majority of which are small, although the Irish fleet also includes some of the largest fishing vessels in Europe, mainly targeting pelagic fish species such as mackerel *Scomber scombrus*, blue whiting *Micromesistius poutassou*, horse mackerel *Trachurus trachurus* and herring *Clupea harengus*. In Ireland, around 12,000 people are employed in fish-related industries (SFPA, 2011).

Since the last MCCIP Annual Report card in 2010, a number of important documents have emerged that help to elucidate the possible impacts of climate change on fisheries, most notably the MCCIP 'Special Topic' report card on Fish, Fisheries and Aquaculture published in May 2012, along with the accompanying paper on 'fisheries' by Cheung *et al.* (2012). This publication received considerable media attention in the UK– with newspaper articles, radio interviews and television programmes all focusing on this topic and referencing the MCCIP report card specifically. In addition, outputs from the NERC-funded Quest-Fish initiative started to emerge in 2012 (e.g. Blanchard *et al.,* 2012; Merino *et al.,* 2012) and have provided insights from coupling complex biogeochemical models of the lower food-web to size-based ecosystem models that encompass fish and fisheries. Finally, a Defra-funded initiative '*The Economics of Climate resilience*' (Defra, 2013) was completed in March 2013, and this included a case study on 'Fisheries'. Specifically this study looked at potential impacts of changes in fish distribution on components of the UK fishing fleet, including detailed consideration of possible climate change adaptation actions.

In this supporting document we draw heavily on these recent documents and we highlight advances in knowledge beyond the last MCCIP assessment on 'fisheries' in 2010.

1. WHAT IS ALREADY HAPPENING?

Changes in fish distribution – response of the fishery

Long-term changes in temperature and/or other ocean variables often coincide with observed changes in fish distribution and fisheries. In an analysis of 50 abundant species in the waters around UK and Ireland, 70% of the fish species were shown to have responded to warming in the region by changing distribution and abundance (Simpson *et al.*, 2011). Specifically, warm-water species with smaller maximum body size have increased in abundance while cold-water, large-bodied species have decreased in abundance.

Recent analyses of Scottish and English commercial catch data spanning the period 1913–2007 has revealed that the peak catches of target species such as cod *Gadus morhua*, haddock (*Melanogrammus aeglefinus*), plaice (*Pleuronectes platessa*) and sole (*Solea solea*) have all shifted distribution latitudinally, albeit not in a consistent way (Engelhard *et al.*, 2011). For example, cod distribution seems to have shifted steadily north-eastward and towards deeper water in the North Sea. Sole seems to have retreated away from the Dutch coast, southwards towards the eastern Channel whereas plaice distribution has moved steadily north-westwards towards the central North Sea (van Keeken *et al.*, 2007). Haddock catches have moved very little in terms of centre of distribution, but their southern boundary has shifted northwards by approximately 130 km over the past 80-90 years. Both Perry *et al.* (2005) and Dulvy *et al.* (2008) demonstrated similar trends using fishery-independent survey data and specifically that distributions of both exploited and non-exploited North Sea fishes have changed markedly over the last 25 years. These authors concluded that further temperature rises are likely to have a profound impact on commercial fisheries. However, significant shifts were only observed for 15 out of the 36 species examined and it is unclear why 21 species studied in Perry's analysis (i.e. the majority) showed no apparent change.

Lynam *et al.* (2010) made use of data from Irish annual groundfish surveys (west of Ireland and Celtic Sea) between 1999 and 2007 and demonstrated that warm-water 'Lusitanian' fish (including sole, John Dory *Zeus faber*, sardine *Sardina pilchardis* and boarfish *Capros aper*) have been increasing on the shelf to the north and west of Ireland, while the 'boreal' community (including cod, haddock, plaice and herring) has been declining to the south. Nicolas *et al.* (2011) have demonstrated a similar trend for estuarine fish, including many commercial species, at a number of sites in Great Britain and Ireland. Among the 15 most common estuarine fish species, 11 displayed a positive difference between current and past mean latitudes suggesting a northward shift of the populations.

Theoretically, in the northern hemisphere, warming results in a distributional shift northward, and cooling draws species southwards. Heath (2007) looked at patterns in international fisheries landings for the whole north-east Atlantic region. Densities of landings of each species were summed by decade and expressed as a proportion of the total. Both northerly and southerly shifts were observed between decades for individual species, however, more species shifted south than north between the 1970s and 1980s (a relatively cool period) and vice versa between the 1980s and 1990s (a relatively warm period). This seems to parallel observed interdecadal changes in sea and air temperatures.

Distribution shifts may have 'knock on' impacts upon commercial fisheries catches because changes in migration or spawning location affect the 'catchability' of individuals to fishing gears. Populations may move away from (or towards) the area where fishing fleets operate and/or where spatial restrictions on fishing are in place. In addition species distributions may migrate across the boundaries where quotas belong to different nations. A notable example has arisen recently as a result of quota allocations between Norway and the EU, and between Iceland, Faroe Islands and the EU. In October 2009 North Sea mackerel appeared to have moved away from the Norwegian Sector (possibly as a result of excessively cold conditions near the Norwegian coast), resulting in disagreements over permissible catches by Norwegian boats in EU waters. Norwegian vessels were forcibly evicted from Scottish waters by UK fishery patrol vessels, once they had caught their allotted quota (see Fishing News, 9th October 2009). At the same time Iceland and the Faeroe Islands unilaterally claimed quota for mackerel (146,000 and 150,000 tonnes respectively in 2011 or 46%), since the species had suddenly attained high abundance in their territorial waters. The debate over equitable quota allocation has raged for more than three years, with EU countries accusing Iceland and the Faeroe Islands of threatening stock sustainability (and potentially the loss of Marine Stewardship Council accreditation). There has also been a threatened retaliatory embargo on imports of all fish products from these countries, that could greatly impact the whitefish (i.e. cod) processing sector in Grimsby. Whether the apparent changes in mackerel distribution are a result of long-term climate change or not remains unclear, however - with climate change in the future, we might anticipate more territorial disagreements of this type.

A similar phenomenon is now occurring in the Irish Sea, English Channel and southern North Sea region with regard to access to anchovy *Engraulis encrasicolus* (Figure 1).

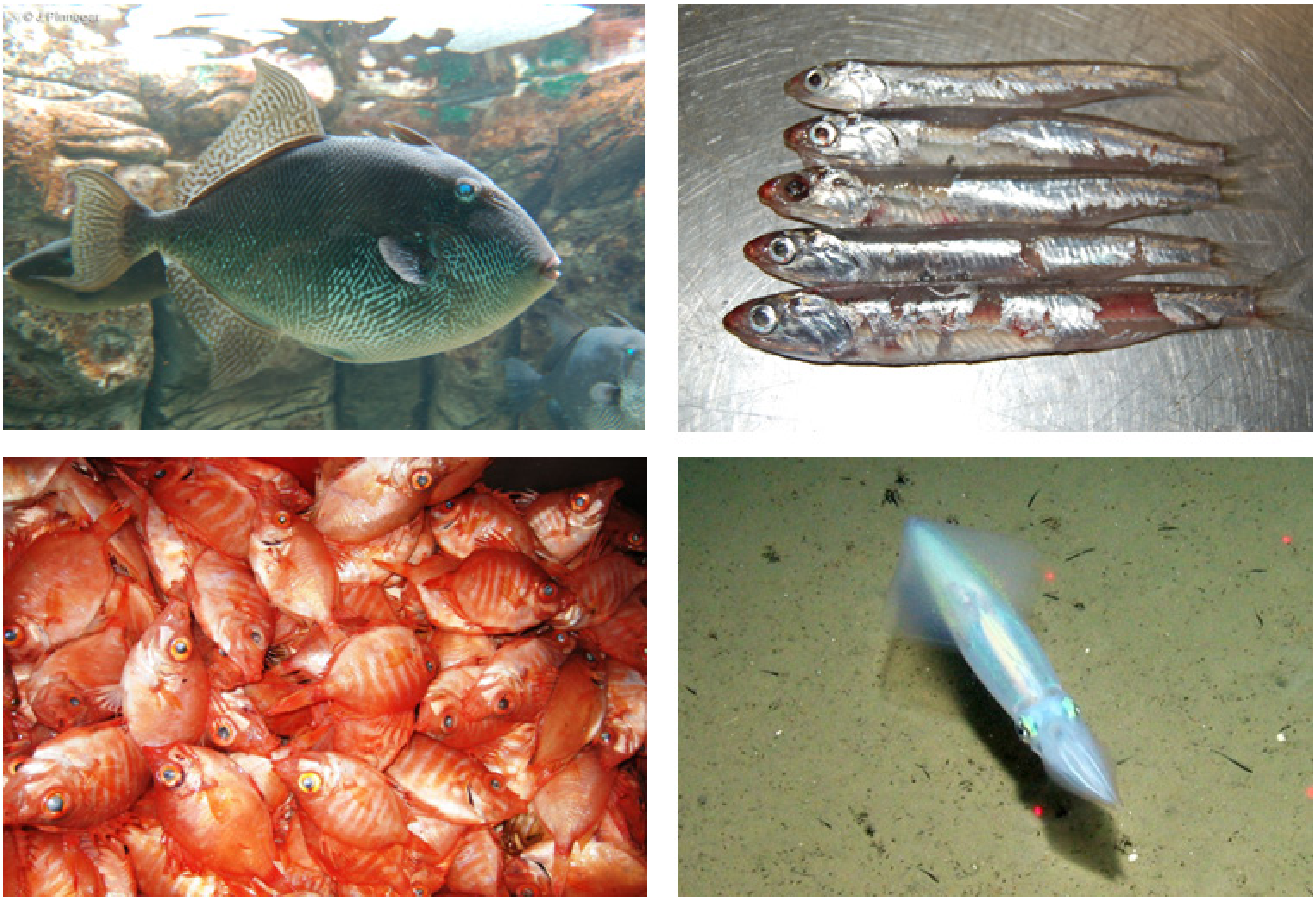


Figure 1: Incoming species of importance to commercial and recreational fisheries. grey triggerfish Balistes capriscus *(top left), anchovy* Engraulis encrasicolus *(top right), boarfish* Capros aper *(bottom left), squid* Loligo forbesi *(bottom right).*

Anchovy stocks are currently depleted in the Bay of Biscay where Spanish and French vessels operate, but are increasing further north along the coasts of Ireland and the UK (and are starting to be targeted by UK and Irish pelagic vessels). Detailed political negotiations are underway to determine whether Spanish and French vessels should be allowed to operate in areas where previously they had no quota, and indeed whether the more northerly distributed anchovy represent the same or a genetically different sub-stock to those in the Bay of Biscay. In 2012, a ground-breaking study was published (Petitgas *et al.* 2012a) drawing on four different strands of evidence: genetic studies, larval transport modelling, survey time series and physical models. This study concluded that anchovy in the southern North Sea (including the Thames estuary) and English Channel are most likely a distinct remnant sub-stock that has always been present, but is now benefiting from greatly improved environmental conditions rather than an invasion of animals from further south. Consequently, according to the rules of 'relative stability' within the EU Common Fisheries Policy, Spanish and French vessels that currently operate in the Bay of Biscay would not necessarily be granted access. The authors argue that a consequence of summer warming in the southern North Sea, may be a spatial and temporal expansion in favourable growth habitats for anchovy. The threshold temperature for anchovy spawning appears to be 14°C in European waters, and modelling suggested that suitable thermal habitats now regularly exist in the southern North Sea for 3 to 4 months each year. Anchovy and sardine abundance has increased considerably around northern Scotland since the early 1990s (Beare *et al.,* 2004) and the authors believe that these long-term changes are related to rising temperatures.

Shifts in species abundance and distributions have, however, compromised the effectiveness of some existing closed areas and other spatial fisheries management measures such as the southern North Sea 'Plaice Box' (van Keeken *et al.*, 2007). In the North Sea, juvenile plaice are typically concentrated in shallow inshore waters and move gradually offshore as they grow. Surveys in the Wadden Sea have shown that 1-group plaice are now completely absent from the area where they were once very abundant. Consequently, the 'Plaice Box' is now less effective as a management measure than was the case 10 or 15 years ago. The boundaries of, and expectations for, marine protected areas (MPA) may need to be 'adaptive' in the future in the context of climate change. In UK and Irish waters there are a number of closed areas aimed at protecting particular fish stocks, and these include many estuarine sites which will experience dramatic changes in temperature and river flow in the next few decades. It is possible that sites where fishery closures are in place, for example to protect juvenile herring or sea bass, may no longer be hospitable for these species in the future. Estimates of future temperature change for five fishery closure areas around the UK and Ireland were provided by Cheung *et al.* (2012). This analysis suggested that most fishery closure areas established under the EU Common Fisheries Policy will experience between 2 and 3°C of temperature rise over the next 80–100 years and consequently it is highly unlikely that the species they are designed to protect will occur in the same numbers as at present.

Link *et al.* (2011) attempted to provide guidelines for incorporating climate-associated fish distribution shifts into fisheries management. The authors noted that the management response will be different, depending on whether: (1) a cohesive stock has simply moved from one locality to another; (2) a stock is simply expanding its distribution – but not necessarily declining anywhere; (3) a stock moves into the area already occupied by another stock but remains behaviourally or genetically distinct; (4) an existing stock that splits into two new sub-populations; or (5) two previously distinct stocks merge, e.g. as a result of mixing due to sea ice melting in the north. A 'decision tree' methodology was proposed (Peterman and Anderson, 1999) to enable fisheries managers to adopt a consistent approach and decide what sort of action might be most appropriate.

Incoming species and new fisheries

Fishermen have witnessed and responded to a number of new opportunities in recent years, as warm-water species have moved into UK and Irish waters and/or their exploitation has become commercially viable for the first time. Notable examples include new or expanding fisheries for seabass *Dicentrarchus labrax*, red mullet *Mullus surmuletus*, john dory, anchovy and squid *Loligo forbesi*.

In Ireland, new fisheries have recently opened up for boarfish *Capros aper*, a small, previously unimportant species (Figure 1) that is converted to fish meal for aquaculture. Landings have grown rapidly from less than 120 t in 2001, to more than 139 000 t in 2010 (ICES, 2011). Both Irish and Danish fishermen have invested in new technologies to successfully catch and land this species and have also invested in scientific research to increase knowledge of the biology and dynamics of this resource (White *et al.*, 2011). This fishery is now worth more than €4 million per year, yet the fishery only became commercially viable following a sudden expansion of the stock in the early 1990s. Boarfish became increasingly prevalent in French and UK survey catches after 1990 (Pinnegar *et al.*, 2002), and this phenomenon has been reported as occurring simultaneously elsewhere in the North Atlantic including the Bay of Biscay (Farina *et al.*, 1997; Blanchard and Vandermeirsch, 2005), the Gulf of Lion (inside the Mediterranean; Abad and Giráldez, 1990) and on offshore seamounts (Fock *et al.*, 2002). In the past boarfish outbreaks had been linked to storms and variability in offshore climate (Cooper, 1952). Their appearance after 1990 across the whole North Atlantic basin may be linked to a series of strong positive anomalies in the North Atlantic Oscillation (NAO) since positive phases of the NAO tend to be associated with above-average temperatures across northern Europe as well as strong westerly winds. In 2011 a Total Allowable Catch (TAC) and national quotas were introduced for boarfish for the first time. Ireland successfully negotiated for ⅔ of the EU boarfish TAC, and in 2012 this amounted to 56,666 tonnes. In 2012, 39 large Irish trawlers caught 53,000 tonnes of boarfish (FishUpdate.com, 10th December) and the Irish Minister for Agriculture, Food and the Marine Environment began negotiations with Chinese seafood companies with regard to exporting large quantities for the human consumption market in China (Fishing News, 14th December 2012). Another species that has increased markedly in Irish and UK waters is the closely related John Dory *Zeus faber* (Briggs *et al.,* 2008). This species is regarded as a 'Lusitanian' species, i.e. of a southern biogeographic affinity, and even within the eastern Mediterranean, the species is associated with warmer water temperatures (Maravelias *et al.*, 2007). Irish fishery landings have increased from 5 tonnes in 1980 to 548 tonnes in 2005 (a 100 fold increase), but declined thereafter to 177 tonnes in 2010. UK landings have increased from 47 tonnes to 432 tonnes over the same period.

Triggerfish (*Balistes capriscus*) (Figure 1) is a warm-water fish that is now occurring in ever greater numbers off the southern coast of the UK. Recreational anglers are increasingly targeting them on inshore wrecks most notably the Royal Adelaide, Chesil Beach (Dorset). Other well-known triggerfish 'hotspots' include Mumbles Pier (near Swansea), Stack Rocks off Littlehaven (Pembrokeshire); Dingle Peninsula (southern Ireland) and off the Sussex and Cornwall coasts. Triggerfish are caught by recreational anglers and pot fishermen in the Channel Islands, especially the north-east corner of Jersey. There have been several stories focusing on this species in recreational angling magazines over the past year (e.g. "Total Sea Fishing" - July 2012) with some evidence that this species is increasing in abundance.

Biomass estimates for seabass *Dicentrarchus labrax* in the eastern Channel quadrupled from around 500 t in 1985, to in excess of 2100 t in 2004/2005, with populations also increasing rapidly in the western Channel, North and Irish Seas (Pawson *et al.*, 2007). This was attributed to an increase in seawater temperatures, especially in the winter and has resulted in a dramatic expansion of seabass fisheries both within the commercial sector, but also in the recreational fishing sector. Seabass are caught by angling on the Scottish east coast, but the northern-most limit of the commercial seabass fishery is around Yorkshire, where trawl-caught fish are increasingly being landed into Scarborough and Whitby. In 2012, 937 t of seabass were landed in the UK, compared with only 140 t in 1984. However, recent evidence (ICES 2012a) seems to suggest that catches may have declined slightly over the past few years, as a result of successive cold winters in 2009/10, 2010/11, 2011/12 with resulting poor recruitment (see below).

Squid numbers are highly uncertain around UK coasts, but there are strong indications that squid (Figure 1) are generally becoming more abundant, possibly in response to a change in climate (Hastie *et al.*, 2009a). Cephalopod populations are suggested to be highly responsive to climate change (Sims *et al.,* 2001; Hastie *et al.*, 2009a) and growth in squid availability in the North Sea is generating considerable interest among fishermen off the Aberdeen coast and around the Moray Firth (Hastie *et al.*, 2009b). Off north-east Scotland, where most of the squid are found, more boats are now trawling for squid than the region's traditional target species, such as haddock and cod (Hastie *et al.*, 2009b). In the English Channel, loliginid squid catches seem to be related to mean sea surface temperature (Robin and Denis, 1999). Temperature appears to influence recruitment strength and overall distribution (Hastie *et al.,* 2009a). Embryonic development duration is closely related to seawater temperature; it increases as temperature decreases and varies between a few weeks (36 days at 16°C) and a few months (60 to 75 days at 12°C, 140 days at 8°C). An optimum temperature range of around 13°C is necessary for normal hatchling development (Jereb and Roper 2010).

The Defra '*Economics of Climate Resilience*' study (Defra, 2013), made use of an August 2012 report by the supermarket, Sainsbury's. This suggests that while the big five (cod, haddock, tuna, salmon and prawns) still dominate the consumer shopping basket, lesser-known species are gaining popularity. Sainsbury's sales data suggest that the following species are increasingly being demanded by consumers: seabass, hake *Merluccius merluccius*, pollock *Pollachius pollachius*, coley (saithe) *Pollachius virens*, tilapia *Tilapia niloticus*. Sainsbury's classify seabass as a particularly popular performer. Sales volumes rose by 57% during 2011 (Sainsbury's, 2012). A study by Waitrose suggested that customers tend to view seabass as being more 'exclusive' than cod, and that it is not seen as an 'everyday food'. A growing number of people now chose seabass when they eat out at UK and Irish restaurants (Defra, 2013).

Year-class strength and implications for fisheries

Recruitment variability, also referred to as the 'year-class strength', is a key measure of the productivity in fish stocks, and is defined as the number of juvenile fish of a given age surviving from the annual egg production to be exploited by the fishery. Empirical data on exploited populations often show strong relationships between recruitment success, fisheries catches and climatic variables. These strong relationships have been demonstrated, for example, for cod (Brander and Mohn, 2004; Cook and Heath, 2005), plaice (Brunel and Boucher 2007), herring (Nash and Dickey-Collas, 2005), mackerel (Jansen and Gislason, 2011), seabass (Pawson, 1992), and scallops (Shephard *et al.*, 2010).

In 2010-2012 new research was published that provides important insight into climate change and the recruitment dynamics of lobster (Schmalenbach and Franke, 2010), herring (Gröger *et al.*, 2010), cod (Beugrand and Kirby 2010; Kristiansen *et al.*, 2011; Olsen *et al.* 2011) and sole (Fincham *et al.,* 2013) in waters around the UK and Ireland. With regard to sole, four out of seven stocks were shown to have exhibited a significant long-term trend towards earlier spawning (Irish Sea, east-central North Sea, southern North Sea, eastern English Channel) at a rate of 1.5 weeks per decade since 1970. Recruitment is critically dependent on the match or mismatch between the occurrence of the larvae and availability of their food (Cushing, 1990), consequently the change in spawning season observed for sole or other species could impact larval survival and thus future fisheries. Conversely, earlier spawning will prolong the growing season of many 0-group fish and may result in an increase in the body size during the 1st winter (Teal *et al.*, 2008). Since winter survival is positively related with body size, 0-group survival may be enhanced for many species under warmer winter conditions (Post and Parkinson, 2001).

In the case of cod, there is a well-established relationship between recruitment and sea temperature (O'Brien *et al.*, 2000; Beaugrand *et al.*, 2003), but this relationship differs with regard to the different cod stocks that inhabit the North Atlantic (Planque and Fredou, 1999). For stocks at the northern extremes, warming leads to enhancement of recruitment, while in the North Sea, close to the southern limits of the range, warmer conditions lead to weaker than average year classes. During the late 1960s and early 1970s, cold conditions were correlated with a sequence of positive recruitment years in North Sea cod and subsequently high fisheries catches for a number of years thereafter (Heath and Brander, 2001). In recent years, however, despite several cold winters, cod have suffered very poor recruitment in the North Sea, although it is unclear whether this is a direct consequence of changed environmental conditions, differences in the availability of planktonic prey items for larval fish or over-fishing of the parental stock (i.e. some sort of 'Allee effect'') (Mieszkowska *et al.,* 2009). Cod populations in the Barents Sea further north, are currently experiencing more favorouable conditions for spawning and have attained their highest levels (2,062,626 tonnnes in 2012) for over 50 years (ICES, 2012b). 90% of cod consumed in the UK are currently imported from either Iceland or Norway (mainly via Grimsby).

For Atlantic mackerel, currently the most valuable fishery in Ireland and the most important fin-fish fishery in the UK, increases in sea surface temperature are known to affect growth, recruitment and migration with subsequent impacts on permissible levels of exploitation (Jansen and Gislason, 2011). Jansen *et al.* (2012) used information on larval abundance (from the Continuous Plankton Recorder) to show that mackerel abundance has declined dramatically in the North Sea since the 1970s and also that the spatial distribution of mackerel larvae seems to have changed. Whether these trends can be ascribed to changes in environmental conditions remains unclear, although development and/or mortality of mackerel eggs is known to be very sensitive to seawater temperature (Mendiola *et al.* 2007). Similarly recruitment in blue whiting (*Micromesistius poutassou*) also seems to be dependent on prevailing climatic conditions. Hátún *et al.* (2009) demonstrated that the position of the North Atlantic subpolar gyre west of the British Isles seems to regulate spawning distribution of blue whiting and hence future recruitment patterns in this important commercial species.

In terms of value, the most important fishery for the UK is that focusing on Norway lobster (scampi) *Nephrops norvegicus* (£111 million, 34,300 tonnes in 2011). *Nephrops* are particularly important in Northern Ireland, where they represent 57% of the total value (33% of the catch by tonnes). Surprisingly little research has focused on this species in relation to climate change. Climate impacts were not found by Zuur *et al.* (2003), who analysed landings-per-unit-effort (LPUE) series for 13 *Nephrops* populations. However, González Herraiz *et al.* (2009) found that LPUE from Spanish trawlers operating on the Porcupine bank (West of Ireland) was negatively related to the NAO index (North Atlantic Oscillation) from 6.5 years before, hence that low Nephrops LPUE values were associated with stormy, warm and wet conditions 6.5 years earlier. Experiments on Irish Sea *Nephrops* demonstrated that, at higher temperatures, larval stages are typically of shorter duration (Dickey-Collas *et al.*, 2000), hinting that climate warming could speed up growth rates and potentially influence recruitment patterns.

For scallops *Pecten maximus*, the most important fishery in the Isle of Man, numbers of young scallops recruiting each year have been positively related to seawater temperature in the spring (Shephard *et al.*, 2010). The gonads of adult scallops also tend to be larger in warmer years, hence warmer conditions in the Isle of Man seems to coincide with higher egg production and improved conditions for scallop fisheries (Shephard *et al.*, 2010).

In Jersey and Guernsey, fisheries tend to target a wide variety of species but the most important are edible crab *Cancer pagurus*, whelk *Buccinum undatum*, scallops, lobster *Homarus gammarus*, rays *Raja* spp. and spider crab *Maja brachydactyla* (1127, 442, 394, 359, 212, 185 tonnes respectively in 2011). Weiss *et al.* (2009) suggest that edible crab exhibits a particularly narrow larval temperature tolerance range and thus that recruitment in this species may be highly vulnerable to the effects of future climate change. By contrast, spider crabs are thought to benefit from warmer seawater temperatures. Early hatching of *Maja brachydactyla* on the French Coast adjacent to the Channel Islands has been related to higher winter-spring sea temperature (Martin and Planque, 2006), and the optimal temperature for spawning and development in this species seems to be around 10-13°C. Fishermen throughout southern England and western Wales (e.g. Cardigan Bay) have reported record numbers of spider crab throughout 2011 and 2012. This echoes a similar 'invasion' that occurred during the hot summer of 2003 (BBC Wales, 23 June, 2003). Over the past 50 years whelk *Buccinum undatum* abundance has also increased dramatically in the English Channel (Hinz *et al.,* 2011) including sites around Jersey and Guernsey even though this is often thought of as a cold-water species (Smith and Thatje 2012). Egg laying and intracapsular development occurs in whelk, across a wide thermal range (2 to 11°C), however development is still possible at temperatures up to 18°C (Smith and Thatje, 2012).

It is important to note that extensive fishing can cause fish populations to become more vulnerable to short-term natural climate variability (e.g. Ottersen *et al.,* 2006) by making such populations less able to 'buffer' against the effects of the occasional poor year classes. Conversely, long-term climate change may make stocks more vulnerable to fishing, by reducing the overall 'carrying capacity' of the stock, such that it might not be sustained at, or expected to recover to, levels observed in the past (Jennings and Blanchard, 2004). In April 2009, the European Commission published a Green Paper that sought views on how the Common Fisheries Policy should be reformed. The 2009 Green Paper recognised that "*[climate] change is already having an impact on Europe's seas and is triggering changes to the abundance and distribution of fish stocks*". It suggests that "*Climate change is an added stress on marine ecosystems which makes a reduction of fishing pressure to a sustainable level even more urgent*".

2. WHAT COULD HAPPEN?

Considerable progress has been made over the past two years with regard to future projections for fish and fisheries, taking into account the effects of climate change. Some of these advances have followed the application of complex ecosystem or fish distribution models (e.g. Cheung *et al.*, 2011; Lenoir *et al.*, 2011; Blanchard *et al.,* 2012; Teal *et al.,* 2012). Other advances have involved detailed economic modelling to determine the potential impact of climate change or ocean acidification on fishing fleets and on regional economies (e.g. Defra, 2013). Although much progress has been made with regard to defining and refining methodologies, there is, however, little consensus with regard to the most appropriate technique to use in different circumstances (see Section 3 on 'level of confidence'), and on the actual trajectory of change for particular fish species or fisheries. Predicting fish responses to climate change is clearly becoming a fashionable endeavour with more papers published in the past three years than were published over the preceding two decades. One constraint on improving the ability to make accurate forecasts is the marked uncertainty surrounding predictions of climate impacts on primary productivity. Some regional climate models (linked to models of phytoplankton) anticipate an increase in system productivity around the UK and Ireland, whereas other models (and recent observations) suggest a decrease. Understanding the direction of change will be critical to improvements in future fish and fisheries models.

The distribution of commercial fish stocks

Modelling strategies for predicting the potential impacts of climate change on the natural distribution of species and consequently the response of fisheries have often focused on the characterization of a species' 'bioclimate envelope' (Pearson and Dawson, 2003). In other words, by looking at the current range of temperatures tolerated by a species, it is possible to predict future distribution, if we know how the physical environment in an area will likely change in the future.

Model simulations suggest that distributions of exploited species will continue to shift in the next five decades both globally and in the north-east Atlantic specifically (Cheung *et al.*, 2009, 2010, 2011; Lindegren *et al.*, 2010). For example, a world-wide analysis has been carried out by Cheung *et al.* (2009) using this technique, based on 1066 commercial fish and invertebrate species. This study suggested that climate change may lead to numerous local extinction events by the year 2050, especially in sub-polar regions, the tropics and semi-enclosed seas, with pelagic species (such as herring and anchovy) moving pole-ward by up to 600km and demersal species (such as cod and haddock) by an average of 223km.

Three climate scenarios were tested using these models, representing high-, medium- and low- range greenhouse gas emissions. Cheung *et al.* (2010), in a follow-up study, estimated future changes in maximum potential catch (a proxy of maximum sustainable yield) as exploited species shift their distribution and marine primary productivity changes. This study suggested that climate change may lead to large-scale redistribution of global maximum catch potential, with an average of 30–70% increase in yield of high-latitude regions (>50° N in the northern hemisphere), but a drop of up to 40% in the tropics. Northern European countries such as the UK and Ireland (at a latitude of 50 to 60°) are projected to gain slightly in maximum potential catch but not as much as countries such as Norway and Iceland. A small overall gain (<5%) is projected in the North Sea if potential effects of ocean acidification are ignored (see below).

Bioclimate envelope models come in different types and varieties, each with different assumptions and biases. Jones *et al.* (2012) applied three different bioclimate envelope models (AquaMaps, Maxent and the Sea Around Us Project algorithm i.e. Cheung *et al.*, 2009) to the same datasets and same geographic region (the North Sea and Northeast Atlantic). Such comparisons provide information about the robustness of projections, and are thus very insightful for spatial planning and developing management and conservation strategies. As indicated by the test statistics, each modelling method produced plausible predictions of habitat suitability for each species (14 commercial fish). However, there were often marked disparities between projected distributions despite exhibiting similar 'goodness of fit'. A conclusion of this work was that authors should not assume that there is necessarily a 'best' model, and that a multi-model ensemble is probably the optimal approach to 'bracket' the level of uncertainty in model predictions. A study by the same authors in 2013 (Jones *et al.,* 2013) applied the same three species distribution models and two sets of climate model projections to explore impacts of climate change on marine species upto 2050. The set of species in the North Sea, including seven threatened elasmobranchs (common skate *Dipturus batis*; angelshark *Squatina squatina*; undulate ray *Raja undulate*; white skate *Rostroraja alba*; sandy ray; thornback ray; *Raja clavata*; nursehound *Scyliorhinus stellaris*) and ten major commercial fishes (cod, haddock, sole, saithe, hake, megrim *Lepidorhombus whiffiagonis*, whiting *Merluccius merluccius*, lemon sole *Microstomus kitt*, monkfish *Lophius piscatorius* and *Nephrops*) were used as a case study. Change in the degree of overlap between commercial and threatened species ranges was calculated as a proxy of the potential threat posed by overfishing through bycatch. The ensemble projections suggested northward shifts at an average rate of 27 km per decade (the current rate is around 20km per decade for common fish in the North Sea, (Dulvy *et al.*, 2008), resulting in small average changes in range overlap between threatened and commercially exploited species. Several additional commercial species (squid *Loligo vulgaris*, seabass, sardine, sprat *Sprattus sprattus*, John dory, anchovy, plaice, herring, mackerel, halibut *Hippoglossus hippoglossus*, red mullet *Mullus surmuletus*) were added to the list as part of the Defra "*Economics of Climate Resilience*" study (Defra 2013). The species predicted to move the furthest and fastest were squid, seabass, anchovy and sardine.

Beaugrand *et al.* (2011) described a new nonparametric ecological niche and used this map the spatial distribution of Atlantic cod and to project the potential impact of climate change on this species. The model suggested a pronounced effect of present-day climate change on the spatial distribution of cod. Projections for the coming decades suggested that cod may eventually disappear as a commercial species from regions where a sustained decrease or collapse has already been documented. In contrast, the abundance of cod is likely to increase in the Barents Sea. Lenoir *et al.* (2011) applied the same non-parametric probabilistic ecological niche model (NPPEN) with multiple explanatory variables (sea surface temperature, salinity, and bathymetry) to predict the distribution of eight fish species upto the 2090s for the north-east Atlantic. This study suggested that by the 2090s horse mackerel and anchovy would show an increased probability of occurrence in northern British waters compared with the 1960s, pollack, haddock, and saithe would show a decrease in southern British waters, and turbot *Scophthalmus maximus* and sprat *Sprattus sprattus* would show no overall change in probability (-0.2 – +0.2) anywhere in British waters.

There are some concerns about the validity of the bioclimate envelope approach (see Jennings and Brander, 2010; Heath *et al.,* 2012). First, it may not be possible to assess temperature preferences from current distributions because the observed distributions are modified by abundance, habitat, pathogen or parasite distribution, predator and prey abundance and competition. Second, there may be barriers to dispersal (although this is typically less of an issue in the sea than on the land) and species will move at different rates and encounter different local ecologies as temperature changes (Davis *et al.*, 1998). A more detailed, physiologically-based approach has been taken by some authors, whereby the detailed dynamics of individual species are modelled, often by linking complex biophysical models (forced with the outputs from Global Climate Models) to sub-routines which replicate the behavior/characteristics of eggs, larvae, juveniles or adults. Teal *et al.* (2012) published a ground-breaking study on plaice and sole in the North Sea. The authors developed a tool to predict size- and season-specific fish distributions based on the physiology of the species and the temperature and food conditions in the sea. This study combined state-of-the-art dynamic energy budget (DEB) models with temperature and food conditions estimated by a biogeochemical ecosystem model (ERSEM) forced with observed climatic data for 2 years (1989 and 2002) with contrasting temperature and food conditions. The resulting habitat quality maps (e.g. Figure 2) were in broad agreement with observed ontogenetic and seasonal changes in distribution as well as with long-term observed changes in distribution (see van Keeken *et al.*, 2007; Engelhard *et al.*, 2011). Other notable models that are based on physiological or behavioural understanding include those of Peck *et al.* (2009), who used outputs from the biophysical circulation model HAMSOM, connected to detailed routines aimed at simulating the drift, distribution and development of fish eggs and larvae in the North Sea, also Hufnagl and Peck

(2011), who used the same methodology to look at climate-driven constraints on larval survivorship and development in Atlantic herring.

Reduced oxygen concentrations in marine waters have been cited as a major cause for concern globally (Diaz and Rosenburg, 2008), and there is evidence (Queste *et al.,* 2013) that areas of low oxygen saturation have started to proliferate in the North Sea. Whether or not these changes are a result of long-term climate change remains unclear and it is also unclear whether such changes will impact commercial fish and fisheries. Unlike parts of the Baltic, which regularly experience complete hypoxia (lack of oxygen), regions of the North Sea only experience low oxygen (65 -70 % saturation, 180-200 μMol dm^{-3}) conditions. Therefore it seems unlikely that fish stocks would suffer major mortality of eggs and larvae (as is the case in the Baltic) but more subtle, non-lethal, effects could become important in the future. Several authors have highlighted how oxygen concentrations and temperature interact and determine 'scope for growth' (e.g. Pörtner and Knust, 2007). *Nephrops norvegicus* juveniles show sub-lethal effects at oxygen concentrations below 156 μMol dm^{-3}, but adults are more robust, although their ability to tolerate other environmental stresses (for example elevated temperatures) is severely compromised (Baden *et al.,* 1990; Eriksson and Baden, 1997). Presumably a proliferation of low oxygen zones around the UK and Ireland could impact fishery productivity, and several authors (e.g. Cheung *et al.,* 2013) have attempted to model such effects.

Recent variants of the bioclimate envelope approach (Cheung *et al.*, 2011, 2013) have attempted to incorporate detailed physiological formulations such as oxygen requirements and 'scope for growth' to overcome some of their perceived earlier shortcomings. The results suggest that these additional factors may cause a reduction in the maximum catch potential by up to 30% in the North Sea by 2050, relative to 2000 under the SRES A2 scenario. In contrast, using a size-structured food web model (Blanchard *et al.*, 2009) to investigate how future temperature and primary production could modulate fisheries potential in the UK, a 24% increase in potential catch was predicted (Blanchard *et al.,* 2012). Possible reasons for the differences in the projected changes from Cheung *et al.* (2011) and Blanchard *et al.* (2012) could be driven by the differences in projected changes in net primary production that drove the two biogeochemical models, which were substantially different. The model used by Cheung *et al.* (2011) anticipated a decrease in net primary production available for fish while the one used by Blanchard *et al.* (2012) projected an increase. A detailed numerical comparison needs to be carried out to gain a better understanding of the differences in the projected catch expectations resulting from the two approaches.

The Blanchard *et al.* (2012) study is one of the main outputs of the NERC-funded QuestFish project. This project attempted to predict the future effects of climate change on fish biomass and production in 11 large regional shelf seas (including the Northwest European Shelf), with and without fishing effects. Changes in potential fish production were shown to most strongly mirror changes in phytoplankton

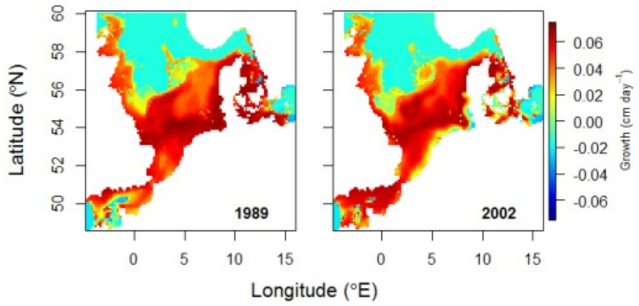


Figure 2: Habitat suitability map of the North Sea for juvenile plaice (approx. 25 cm long) shows that since 1989, the coastal zones have changed from red (high potential growth rate for juvenile plaice) to yellow (low growth rate) and locally green/ blue (negative growth rate). The model devised by Teal et al. *(2012) suggests that the coastal zones have become an unsuitable habitat for juvenile plaice since 2002.*

production. An advantage of the modelling approach taken by Blanchard *et al.* (2012) is the ability to examine the relative effects of climate change and fishing simultaneously. Changes in primary production and temperature affected growth rates and fish production, altering the responses of ecosystems to fishing. Also, in keeping with empirical studies of fish populations and theoretical size-spectrum models, fishing effects were anticipated to cause ecosystems to become more variable through time, due to reductions in size structure and shifts towards smaller size and higher growth rates (i.e. removal of large slow growing, more fecund individuals, proliferation of smaller animals). Heavily fished ecosystem states were found to be less resilient to climate change compared with unexploited ecosystems. Another important output from the QuestFish project, building directly on the work of Blanchard *et al.* (2012), was the bio-economic study of Merino *et al.* (2012). In this study the authors used predictions of changes in global and regional climate (IPCC emissions scenario A1B), marine ecosystem and fisheries production estimates from high resolution regional models, human population size estimates from the United Nations, fishmeal and oil price estimations, and projections of the technological development in aquaculture feed technology, to investigate the feasibility of sustaining current and increased per capita fish consumption rates up to 2050.The model estimated that climate change will result in a small (6%) global increase in the potential catches of "large" fish by 2050. This estimate corresponds to the fraction used for direct human consumption and is based on predicted responses of fish communities to changes in temperature and primary production. Using the production in the "small" size range for the top twelve fishmeal-producing countries as a proxy for global fishmeal production which is mostly used as input in aquaculture, the authors predicted a potential growth of ca. 3.6% of fishmeal by 2050, with high latitude countries predicted to benefit from increases in production (e.g. Norway, Iceland), while low latitude and tropical regions were expected to suffer production decreases (e.g. Peru). Marine ecosystems may be able to sustain current and increased per capita consumption rates through 2050, provided that effective fisheries management measures are implemented and that significant technological adaptations are developed in aquaculture to increase the efficiency at which wild fish is used to produce cultured fish.

The productivity of commercial fish stocks

In terms of predicting climate change impacts on future fisheries productivity (recruitment, stock biomass, maximum sustainable yield etc.), the greatest amount of effort has tended to be focused on cod and the fisheries that are dependent on this species. For example, Drinkwater (2005) provided a regional overview and used temperature-recruitment relationships from Planque and Frédou (1999) together with outputs from Global Circulation Models (GCMs) to predict possible responses of cod stocks throughout the North Atlantic. According to this study, cod stocks in the Celtic and Irish Sea are expected to disappear altogether by 2100, while those in the southern North Sea and Georges Bank will decline. Elsewhere, stock productivity will increase (e.g. around Iceland). Cod will likely spread northwards along the coasts of Greenland and Labrador, occupying larger areas of the Barents Sea, and may even extend into some parts of the Arctic Ocean. Spawning sites will be established further north than is currently the case and it is likely that spring migrations will occur earlier and autumn returns will be later. The Drinkwater *et al.* (2005) model is, however, potentially misleading, among other things because it does not take account of seasonal temperature cycles. e.g. the Celtic Sea has far lower summer temperatures than the southern North Sea and the cod spawning stock biomass in this region has actually increased in recent years (from 3495 in 2005 to 25,453 in 2012) as a result of several strong year classes, contrary to expectations. Petitgas *et al.* (2012b) provide a recent review of climate change impacts on the complex life cycles of fish including cod, however these authors acknowledge that much more work is required in order to provide truly robust projections.

Clarke *et al.* (2003) used projections of future North Sea surface temperatures and estimated the likely impact of climate change on the reproductive capacity of the cod stock, assuming that the high level of mortality inflicted by the fishing industry (in 2003) continued into the future. In a re-analysis by Kell *et al.* (2005), the authors modelled the effect of introducing a 'cod recovery plan' (as being implemented by the European Commission), under which catches were set each year so that stock biomass increased by 30% annually until the cod stock had recovered to around 150,000 tonnes. The length of time taken for the cod stock to recover was not greatly affected by the choice of climate scenario (generally around 5-6 years). However, overall productivity was impacted, and stock biomass (SSB) was predicted to be considerably less in the future than would have been the case assuming no temperature increase (251,035 tonnes compared to 286,689 tonnes in 2015). The overall message from this study was that in the short term, climate change has little effect on stock recovery, which depends instead upon reducing fishing effort to allow existing year classes to survive to maturity. In the longer term, climate change may have a greater effect on stock status. Lindegren *et al.* (2010) has since used similar methodologies to explore the impacts of climate change and a range of fishery management scenarios in the Baltic Sea.

Cook and Heath (2005) examined the relationship between sea surface temperature and recruitment in a number of North Sea fish (cod, haddock, whiting *Merlangius merlangus*, saithe, plaice, sole). These authors concluded that if the recent warming period were to continue, as suggested by climate models, stocks which express a negative relationship with temperature (including cod) might be expected to support much smaller fisheries in the future. In the case of cod, climate change has been estimated to have been eroding the maximum sustainable yield at a rate of 32,000 t per decade since 1980. Calculations show that the North Sea cod stock, could still support a sustainable fishery under a warmer climate but only at very much lower levels of fishing mortality, and that current 'precautionary reference' limits or targets (e.g. FMSY), calculated by ICES on the basis of historic time-series, may be unrealistically optimistic in the future. The recruitment formulations suggested by Cook and Heath (2005) were used as the basis for further analysis in the 2012 UK Climate Change Risk Assessment (CCRA) (see Pinnegar *et al.*, 2012). A simple age-based population model was constructed for the North Sea and in every case the model projected recovery of populations, even at the current level of North Sea fishing mortality. Long-term yields of cod and plaice were projected to be lower in the future when climate change was taken into account whereas yields of whiting and saithe were expected to be enhanced.

Ocean acidification

Ocean acidification (OA) may have direct and indirect impacts on the recruitment, growth and survival of exploited species (Fabry *et al.*, 2008) and some species may become more vulnerable to OA with increases in temperature (Hale *et al.*, 2011). The impacts are suggested to be particularly apparent for animals with calcium carbonate shells and skeletons such as molluscs, some crustaceans, and echinoderms (Gazeau *et al.*, 2007; Cooley and Doney, 2009; Hendriks *et al.*, 2010; Kroeker *et al.*, 2010), but research shows large variations between and within taxonomic groups.

A preliminary assessment in 2012 estimated the extent of economic losses to the UK shellfish industry under ocean acidification (Pinnegar *et al.*, 2012). Four of the ten most valuable marine fishery species in the UK are calcifying shellfish and the analyses suggested losses in the mollusc fishery (scallops, mussels, cockles, whelks, etc.) could amount to £55–379 million per year by 2080 depending on the CO_2 emission scenario chosen. In addition, a further £59.8–124.6 million might be lost from the shellfish aquaculture sector (oysters, mussels etc.) assuming future CO_2 concentrations increase from the current level of ~380 ppm to ~740 ppm (pH 7.9–8.0). Thus, there is a clear economic reason to improve our understanding of physiological and behavioural responses to ocean acidification and techniques for modelling the up-scale implications. The most important shellfish species in the UK and in Ireland is langoustine (scampi) *Nephrops norvegicus*. The possible impact of

OA on *Nephrops* is unclear. *Nephrops* live in burrows with relatively poor ventilation and therefore regularly experience periods of elevated CO_2 as a result of respiration. In addition, preliminary analyses of sediment pH in *Nephrops* areas (carried out at Cefas) has revealed very dramatic decreases in the top few centimetres of sediment and thus burrowing animals could be exposed to pH conditions of 6.7 or even lower on a regular basis. As part of the NERC, Defra and DECC – funded UK Ocean Acidification Programme (UKOA), experiments are currently underway within the UK to look at direct physiological responses of herring, scallops and lobsters to ocean acidification. However, it is suggested that indirect (food-web) effects may be more important for fin-fish, than direct physiological impacts (Le Quesne and Pinnegar, 2012). So far few studies have attempted to investigate the potential "bottom up" impacts of ocean acidification on marine food-webs, and hence on fisheries (although see Kaplan *et al.,* 2010). Cooley and Doney (2009) in their economic analysis, did account for "fish that prey directly on calcifiers". These authors suggest that the indirect economic consequences could be substantial. Pinnegar *et al.* (submitted) carried out a modelling study of whether or not a hypothetical reduction in echinoderm or mollusc biomass in the North Sea (as a result of ocean acidification) would likely have consequences for fin-fish biomass, fishing fleets and for fishery yields. This study concluded that fisheries would probably be impacted very little in terms of catches, and value. In particular, catches in the beam and otter trawl fleet might even be enhanced. Most fin-fish species are able change their diet to target other prey types that proliferate under ocean acidification (for example polychaetes and amphipods) – hence catastrophic predictions regarding the economic consequences of ocean acidification could be over-stated. However, it is not clear if early life-history stages of fin-fish could be impacted by anticipated changes in the zooplankton as a result of OA, or whether subtle changes in fish behaviour as a result of OA (Munday *et al.,* 2010) might also be important. Clearly, more modelling work is needed before definitive conclusions can be drawn about whether or not fishermen and society as a whole will be significantly affected by ocean acidification.

3. KNOWLEDGE GAPS

The top priority knowledge gaps that need to be addressed in the short term to provide better advice to policy makers are:

a. An assessment of the social and economic implications of climate change on fishing fleets and dependent economies in the UK and Ireland. The fishing industry itself has repeatedly questioned scientists about the challenges they are likely to face in the future, and the UK Climate Change Act (which became law on 26 November 2008) requires that a national adaptation programme be put in place and reviewed every five years which includes a thorough assessment to identify the most pressing climate change risks. Attention should be paid to identifying the 'winners' and 'losers' that might result from future climate change including the particular fleets and ports that would be affected.

b. Improved insight into the possible threat posed by ocean acidification, particularly with regard to the UK and Irish shellfish industry. The UK Ocean Acidification Research Programme (UKOA) has begun a series of laboratory experiments looking at physiological impacts on particular organisms. Greater thought should be dedicated towards 'scaling up' from laboratory experiments to the population-level implications, understanding indirect consequences and quantifying possible economic losses to fisheries or aquaculture.

Better wind and storm projections are needed and improved understanding of how any changes in these variables might impact maritime safety, and/or access to fishery resources. Fishing operations can be greatly influenced by prevailing weather conditions. If storm severity or frequency changes then fishing livelihoods could be heavily impacted (e.g. Westlund *et al.* 2007).

4. SOCIO-ECONOMIC IMPACTS

UK and Ireland

So far, surprisingly little research has been directed towards understanding the future implications of climate change for fishing fleets, fishermen, coastal economies and society. This is certainly the case within the United Kingdom and Republic of Ireland. There are a number of studies that have set out to investigate the vulnerability and adaptive capacity of the fisheries sector at a global scale (McClanahan *et al.,* 2008; Allison *et al.,* 2009). However, until recently there has been little directed analysis at the local scale of how climate variability and change is affecting the lives and livelihoods of those involved in the UK and Irish fishing and fish processing sectors. Fisheries managers and fisherfolk have historically had to adapt to the vagaries of weather and climate. Uncertainty is inherent in fisheries management, so there is an expectation of change and a stock of knowledge and experience of coping with it and adapting to it (Miller *et al.,* 1992). Badjeck *et al.* (2010) have argued that diversification is a primary means by which individuals can reduce risk and cope with future uncertainty. There is some evidence that the inability of fishing households to adapt to environmental change is not only linked to the level of poverty (or ability to raise capital), but also to the "specialization trap" where fisherfolk overly rely on one species or activity.

In 2012 Defra commissioned its '*Economics of Climate Resilience*' (ECR) project in response to perceived shortcomings or uncertainties in the national Climate Change Risk Assessment (CCRA). This study included a detailed assessment of whether or not the UK fish catching sector can be expected to adapt to the opportunities and threats associated with future climate change. It built heavily upon the analyses of Jones *et al.* (2012, 2013) – see above, and highlighted increases of habitat suitability for a number of species currently emerging in UK waters which could offer future commercial opportunities. The ECR report looked for examples of current adaptation by the sector, by focusing on species increasing in the UK EEZ, such as anchovy, squid, seabass, and also past increases in, scallops, boarfish, and hake. The UK fishing industry includes operators of vessels of varying adaptive capacity and capability. The ability of some segments within the sector to adapt is likely more constrained than others, notably for small vessel operators. Such operators face constraints on their ability to travel distances to reach their favoured fish stock, the time they are able to be at sea and their access to the rights to catch particular species. The key adaptation actions the UK fishing industry is likely to make include:

1. Travelling further to fish for current species, if stocks move away from UK ports.

2. Diversifying the livelihoods of port communities, this may include recreational fishing where popular angling species become locally more abundant (e.g. sea bass).

3. Increasing vessel capacity if stocks of currently fished species increase.

4. Changing gear to fish for different species, if new or more profitable opportunities to fish different species are available.

5. Developing routes to export markets to match the changes in catch supplied. These routes may be to locations (such as southern Europe) which currently eat the fish stocks which may move into the UK EEZ.

6. Stimulating domestic demand for a broader range of species, through joined up retailer and media campaigns.

The uncertainty around the projected impacts of warming sea temperatures make appropriate localised actions difficult to determine in advance, and highlight the need for the sector to be flexible to future uncertainty. Key barriers and constraints to autonomous action identified in the ECR report include:

• The capacity of vessels to travel (distance and time at sea); a barrier for the smaller inshore fleets.

• The cost of investing in new nets and gear where it may be required for a particular species (although there is some funding available through industry grants).

• The speed of the sector to adapt is constrained by the process of setting quotas for total allowable catch of particular species. This process is lengthy and backward looking so there is a risk that quota allocations restrict fishing activity where stocks are increasing or changing their distribution.

• Quota allocations are based on historic levels of catch and therefore can create incentives for maladaptation. Particularly for species not under quota, where their emerging abundance creates expectations of future quota restrictions (a race to establish a 'track record').

• Strong domestic consumer preferences for a limited range of species is a major constraint inhibiting the ability of UK suppliers to benefit from potential opportunities.

In the UK, fisheries contribute less than 0.07% to national GDP (0.39% in Scotland, 0.11% in Northern Ireland, 0.07% in Wales and 0.03% in England), however, there are some regions where fisheries provide the mainstay of employment and are vitally important to the local economy. While fishermen account for a small percentage of the national workforce (0.2% in Scotland and 0.1% in England and Wales), national fishery statistics suggest that dependency is as high as 24% in the Western Isles, and 20% in Fraserburgh (NE Scotland), Brixham and Newlyn (SW England). In the Isle of Man agriculture and fishing provide 2.0% of employment and 0.08% of GDP. In the Channel Islands, agriculture and fishing provide 2.6% of employment and 1.3% of GDP, hence impacts of climate change on the fishing industry will only ever have a small impact on the economy as a whole. In Ireland fishing supports 0.6% of employment and 0.5% of annual GDP, however local dependence on the fishing industry is particularly high in areas such as Killybegs (County Donegal). In 2009 the total turnover in this area was around €250 million with 82% of regional activity being attributed to the fisheries sector (Macfadyen *et al.*, 2010). Kopke and O'Mahony (2011) provided an overview of adaptive capacity, barriers to adaptation and information needs in the Irish fisheries sector.

Global Analyses

The ACACIA report written by Des Clers (University College, London) and Brander (ICES) in 2000 provided the European impact assessment for the IPCC Third Assessment (2001) and included a short chapter on Fisheries. Some of the economic and social implications of climate change for fisheries were set out in chapter 9 of the ACACIA report (ACACIA, 2000) from which Table 1, showing supply side and demand side adaptations of fisheries to climate change impacts, has been taken. Many of the same adaptation options were also highlighted by McIlgorm *et al.* (2010) who reviewed how fishery governance may need to change in the light of future climate change.

Table 1: Adaptations of fisheries to climate change (from chapter 9 of ACACIA, 2000)

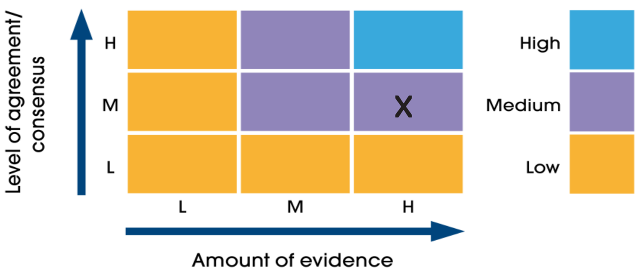
Impact	Supply side	Demand side
Fish distribution changes	• Revise fishing rights allocation • Allocate species combinations (MSC) and access at ecosystem level • Economic incentives to switch target species or use other gear	• Changes in consumer preferences driven by eco-labelling and certification (MSC accreditation) • Quality labelling (the last wild food…)
Decreased productivity	• Improve product quality and life • Reduce production inefficiencies and waste • Introduce ecosystem/portfolio management • Switch to new species • Increase imports	• Taxes on ecological costs of fish • Advertise unique nutritional value of fish, Inform customers

Governments have implemented various measures to manage fisheries, both to conserve fish stocks and to help communities that depend on fishery resources adapt to changes caused by overfishing and other factors. Measures include buybacks, transferable quotas, and investments in alternative sources of employment and income. Sumaila and Cheung (2009) attempted to establish the costs of adaptation to climate change in the fisheries sector worldwide. Adaptation to climate change is likely to involve an extension of such policies. In Europe (including the UK) the estimated annual cost of adaptation was between 0.03 and 0.15 $ billion. As compared to 1.05 - 1.70 $ billion of anticipated annual adaptation costs in East Asia and Pacific. Grafton (2010) provided a more general review of adaptation to climate change in marine capture fisheries including methods for risk and vulnerability assessment.

Allison *et al.* (2009) provided an assessment of the 'vulnerability' of 132 national economies to potential climate change impacts on their capture fisheries using an indicator-based approach. Vulnerability to climate change depends upon three key elements: exposure (E) to physical effects of climate change, the degree of intrinsic sensitivity of the natural resource system or dependence of the national economy upon social and economic returns from that sector (S), and the extent to which adaptive capacity (AC) enables these potential impacts to be offset. In a further development of this work, Cefas scientists (as part of the recently completed NERC 'Quest-GSI' project) used a number of different Global Climate Models (GCMs) that provided outputs of sea surface temperature and improved formulation of fisheries catches. In terms of vulnerability, the authors ranked the UK as 215th out of 225, Ireland as 223 out of 225 with good adaptive capacity and a very small anticipated impact. The Channel Islands were ranked 208 and the Isle of Man was ranked 218th.

5. CONFIDENCE ASSESSMENT

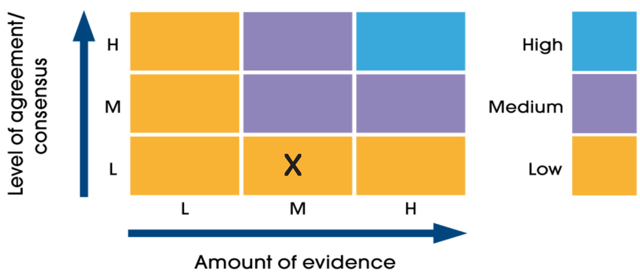
What is already happening?



In general there is probably more information available about fish and changes in the fishing industry than any other maritime sector or commodity. Fish resources (especially those in the North Sea) have been intensively monitored for more than 100 years and authors have been discussing links to climate and weather since the 1914 (Hjort, 1914). However, there is a surprising lack of studies that have attempted to quantify how changes in fish production or distribution might manifest themselves as impacts upon commercial fishing yields, profits or implications for society generally. Despite the large amount of data available, there is little consensus regarding whether or not climate change is having an impact on fisheries. Indeed recent crises in the European fishing industry have attracted considerable public interest and prompted a number of independent enquiries into the causes of the problems (Anon., 2004). While these enquiries have concluded that fishing is the main factor causing the decline of whitefish stocks such as cod and plaice, there remains a popular perception, particularly among fishermen, that environmental factors, such as climate change, are a significant cause (see Fishing News, March 12th 2004; and Schiermeier, 2004). A good example of the contentious nature of this debate relates to the management of Atlantic mackerel. Scientists disagree about whether or not the stock has migrated/shifted westwards towards Iceland or simply expanded its range, and whether or not any changes are a result of climate change. Similarly opinions regarding the impacts of ocean acidification range from wholesale degradation of marine ecosystems and fisheries to negligible impacts with minimal economic consequences (Hendriks *et al.*, 2010; Kroeker *et al.* 2010; Turley *et al.* 2010). Clearly more research is needed to resolve such conflicts, even though substantial progress has been made in recent years (as described above).

Many new studies have been published over the past 2-3 years and thus the amount of available evidence is judged as being 'high', however the level of agreement and consensus is still judged as being 'medium' and thus **the overall assessment has not changed from the 2010/11 report card**. Scientists currently disagree on the causes of apparent northwards shifts in fish distribution in the North Sea, and there are many competing but not mutually exclusive hypotheses to explain this phenomenon (see Rijnsdorp *et al.* 2009). The most frequently voiced are: (1) warming causes species to expand northward, (2) fishing pressure has been consistently higher in the south compared to northern North Sea, causing higher mortality in the south and hence, an apparent overall distribution shift; (3) other important drivers, e.g. habitat degradation or eutrophication may be having an effect.

What could happen?



With regard to understanding what might happen in the future, there are even fewer studies available and consequently there is even less consensus among researchers and policy makers concerning necessary adaptation strategies and policies. However much progress has been made in the past 2-3 years and the evidence-base has strengthened significantly. There have been several studies which have attempted to predict future fish distribution, fishery yield or spawning stock biomass of particular species, but this has rarely (if ever) been translated into consequences for fisheries and/or society. The knowledge-base is particularly uncertain with regard to the possible future implications of ocean acidification. Consequently **the level of confidence has not changed** from that stated in the 2010-2011 Annual Report Card.

CITATION

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