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Impacts of climate change on fisheries and aquaculture

Synthesis of current knowledge, adaptation and mitigation options

Chapter 5: Climate change impacts, vulnerabilities and adaptations: North Atlantic and Atlantic Arctic marine fisheries

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KEY MESSAGES

- For many countries bordering the North Atlantic, fisheries contribute very little to national gross domestic product (GDP) and per capita seafood consumption is low, hence, fisheries are not primarily concerned with maintaining food security. In Greenland, Iceland and the Faroe Islands however, fishing remains a nationally important activity.
- Throughout the North Atlantic there are specific communities, towns or regions that rely heavily on fisheries for employment and income-security. Indigenous peoples of the Atlantic Arctic such as the Inuit in Canada, Kalaallit in Greenland, the Saami in Norway and the Russian Federation are heavily reliant on fisheries to maintain cultural heritage and food security and are especially vulnerable to climate change.
- Large-scale changes in the distribution and productivity of commercial fish species have been observed on both sides of the North Atlantic and shifts in some key fisheries targets have created major challenges for resource allocation between different countries and fleets.
- For some species such as Atlantic cod, climate change can have opposite impacts on recruitment and productivity, depending on where the stock is located. Warmer temperatures are associated with poor recruitment of cod in the Celtic Sea, Irish Sea and North Sea, but good recruitment in the Barents Sea and Labrador coast of Canada.
- Dramatic, long-term decreases in ocean pH have been observed throughout the North Atlantic over multiple decades. Continued declines in pH are anticipated and the consequences for commercial shellfish or early life stages of important finfish remain unclear.
- Major biogeographical shifts in zooplankton have been documented in response to warming. Warm-temperate, pseudo-oceanic species experienced a poleward shift of about 10° of latitude or 23 km/yr for the period 1958 to 2005. Continued shifts in these prey species may pose threats to the productivity of some fish stocks.
- Large-scale redistribution of maximum fisheries catch potential is projected by 2055 under a business as usual scenario, including a 30 percent to 70 percent increase in yield of high-latitude regions, particularly the exclusive economic zone (EEZ)

regions of Norway and Greenland and the Grand Banks of Canada, and decreases at latitudes lower than around 50 °N.

- A wide diversity of climate change adaptation measures has been tested, applied and advocated in the North Atlantic region. These have tended to focus on capacity building within the sector, policy measures, building resilience through a reduction in other stressors, developing alternative markets or livelihoods and protecting critical infrastructure used by the fishing industry. Institutional, legal, financial and logistical barriers to successful adaptation have been encountered on both sides of the Atlantic.

5.1 REGIONS AND FISHERIES OF THE NORTH ATLANTIC

The North Atlantic (FAO major fishing areas 21 and 27) is a huge, ecologically, socially and economically diverse region spanning from the Azores in the south (37 °N) with average sea temperatures around 24 °C to Spitzbergen and north Greenland in the high Arctic (78 °N) with temperatures well below freezing (see Figure 5.1). It is bounded by two continents (North America and Europe).

The Northwest Atlantic (FAO major fishing area 21) has large, industrial fisheries active on the continental shelf such as the Grand Banks of Newfoundland, the Scotian Shelf and Georges Bank. Historically, fisheries mainly targeted demersal groundfish, primarily gadoids and flounders via otter trawling and fixed gears (e.g. gillnet, bottom longline). The main targets of pelagic trawlers (purse seiners) are Atlantic herring (*Clupea harengus*) and mackerel (*Scomber scombrus*). Other fisheries have increased in recent decades such as those on squids (shortfin [*Illex illecebrosus*] and longfin [*Doryteuthis pealeii*]). International waters support important fisheries for redfish (*Sebastes* spp.), flatfishes (yellowtail flounder [*Limanda ferruginea*] and American plaice [*Hippoglossoides platessoides*], Greenland halibut [*Reinhardtius hippoglossoides*]), cod (*Gadus morhua*) and capelin (*Mallotus villosus*). The size of groundfish fishing fleets has decreased in the most recent decades. The fleet in the United States of America decreased from 1 000 vessels in the mid-1990s to 400 vessels in 2012 (Thunberg and Correia, 2015). The largest decrease was a 69 percent decline in the number of limited access vessels, with an 80 percent decline in the Gulf of Maine. The share of small (less than 10 metre) and large (greater than or equal to 23 metres) vessels declined and increased, respectively. The diversity and size of gear (trawl, gillnet, hook) used by vessels fishing groundfish in the United States of America has remained relatively stable (Thunberg and Correia, 2015). In Atlantic waters off Canada, landings of groundfish decreased from 50 percent to 13 percent of the total national catch from 1991 to 2011 while the economic value of total fisheries catches increased as a result of a large upsurge in the landings of valuable shellfish (lobster [*Homarus americanus*], snow crab [*Chionoecetes opilio*] and shrimps) captured off Nova Scotia, Newfoundland and Labrador. More than 90 percent of the approximately 15 000 registered fishing vessels operating in Atlantic waters off Canada are small (less than 14 metres) and two-thirds of all landings in this region were from pots and traps (Department of Fisheries and Oceans Canada (DFO), Canadian Fisheries Statistics, 2011 to 2012[1]).

Most of the fisheries in the Northwest Atlantic are managed within the exclusive economic zones (EEZ) of the United States of America or Canada by National Oceanographic and Atmospheric Administration (NOAA) National Marine Fisheries Service (NMFS) and DFO, respectively, as well as Greenland. Fishing rights on the Flemish Cap and all other deeper waters are governed by treaties maintained by the Northwest Atlantic Fisheries Organization (NAFO). Arctic fisheries take place mostly within the ice-free EEZs of the subarctic/boreal seas (see Blomeyer *et al*., 2015). The most important fisheries in the Atlantic Arctic are in the Barents Sea (FAO

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[1] http://www.dfo-mpo.gc.ca/stats/commercial/cfs/2012/cfs12-eng.htm

fishing area 27.1), the Norwegian Sea (FAO fishing area 27.2), and around Greenland and Iceland (FAO fishing areas 27.5 and 27.14), for cod, haddock (*Melanogrammus aeglefinus*), Atlantic herring, but also exclusively Arctic species including capelin, Greenland halibut, northern shrimp (*Pandalus borealis*) and polar cod (*Boreogadus saida*). In subarctic waters, the Norwegian and Barents seas have the greatest numbers of exploited species (more than 20 species each) including krill (*Thysanoessa inermis* and *T. longicaudata*) and copepods (*Calanus finmarchicus*). In the 1970s, polar cod was intensively fished by former Union of Soviet Socialist Republics, Norwegian, Danish and German Democratic Republic fleets in the Barents Sea, White Sea and in Soviet waters. Landings have declined from 348 000 tonnes in 1971 to less than 70 000 tonnes today with most of the current catches by the Russian Federation fleet (Blomeyer *et al.*, 2015). In the Barents Sea, capelin is targeted using pelagic trawls and purse seines and the species is also bycatch in fish and shrimp trawls. Strong fluctuations in the catches of capelin coincide with cycles of the Arctic Oscillation or Northern Annular Mode.

Atlantic cod is caught mainly with bottom otter trawls and pelagic trawls. The major fishing grounds for Atlantic cod are around Iceland, in the Barents Sea, off Newfoundland and West Greenland, with Iceland and Norway accounting for the biggest share of landings in recent years. Greenland halibut is caught on the deep shelf, mainly with bottom longlines and gillnets. Almost all of the Northeast Greenland halibut caught are by the Norwegian and Russian Federation fleets (Blomeyer *et al.*, 2015).

Fishing is of high economic importance for a few Northeast Atlantic (Northwest European) countries, notably Iceland, Greenland and the Faroe Islands. Fisheries products contribute 20 percent of national GDP for the Faroe Islands and Greenland and over 90 percent of their exports. Although, fishing accounts for less than one percent of Europe's total GDP, income and employment from fishing and related activities can be very important to certain fishery-dependent towns and coastal villages (see Section 5.6.1, below). Fisheries in the Northeast Atlantic are regulated through a combination of arrangements. These include national policies and regulations, the European Union (EU) Common Fisheries Policy, bilateral and multilateral agreements between countries with shared stocks, and measures adopted by the three regional fisheries management organizations: the North East Atlantic Fisheries Commission (NEAFC), the International Commission for Conservation of Atlantic Tunas (ICCAT), and the North Atlantic Salmon Conservation Organization (NASCO).

The main fishing nations dependent on the North Sea subregion (FAO fishing area 27.4) are the United Kingdom of Great Britain and Northern Ireland, Denmark, the Netherlands, Belgium, Germany and Sweden (STECF, 2017). The most valuable species include Atlantic mackerel, Atlantic cod, Atlantic herring, common sole (*Solea solea*), European plaice (*Pleuronectes platessa*) and brown shrimp (*Crangon crangon*). In 2015, the EU member state fleet had 4 955 vessels operating in the North Sea region with 47 percent from the United Kingdom of Great Britain and Northern Ireland. In 2015 Denmark, France and United Kingdom of Great Britain and Northern Ireland together accounted for around 73 percent of the total days at sea. Around 41 percent of the days at sea were undertaken by small-scale coastal vessels using passive gears. In 2015, the weight and value of landings generated by the North Sea fleet amounted to approximately 1.66 million tonnes and EUR 1.8 billion (equivalent to approximately USD 2.2 billion), respectively (STECF, 2017). In 2015, Atlantic herring (386 000 tonnes) was the most important species in terms of weight. Landings of European sprat (*Sprattus sprattus*), Atlantic mackerel, sandeels (*Ammodytes* spp.) and European plaice were the next most important species in terms of weight. In terms of value, the most important species were Atlantic mackerel followed by Atlantic cod, Atlantic herring, common sole, European plaice, common shrimp and Norway lobster (*Nephrops norvegicus*) (STECF, 2017).

The major players in the Northeast Atlantic margin subregion (FAO fishing areas 27.6–9) are the Spanish, French, United Kingdom of Great Britain and Northern Ireland, Portuguese and Irish fleets, with the latter two having the highest dependency on the region for production. The most important species include Atlantic mackerel, horse mackerel (*Trachurus trachurus*), hake (*Merluccius merluccius*) and Norway lobster (STECF, 2017). The ten EU member state fleets operating in the region collectively numbered over 14 600 active vessels in 2015 with the Spanish fleet comprising 37 percent of the total. The weight and value of landings generated by the Northeast Atlantic fleet amounted to approximately 1.4 million tonnes and EUR 2.4 billion (equivalent to approximately USD 2.9 billion), respectively (STECF, 2017). The main species landed in terms of weight were small pelagic species, including Atlantic mackerel, blue whiting (*Micromesistius poutassou*), followed by European hake and horse mackerel. The most valuable species were European hake followed by Atlantic mackerel, Norway lobster as well as monkfish (*Lophius piscatorius*) (STECF, 2017).

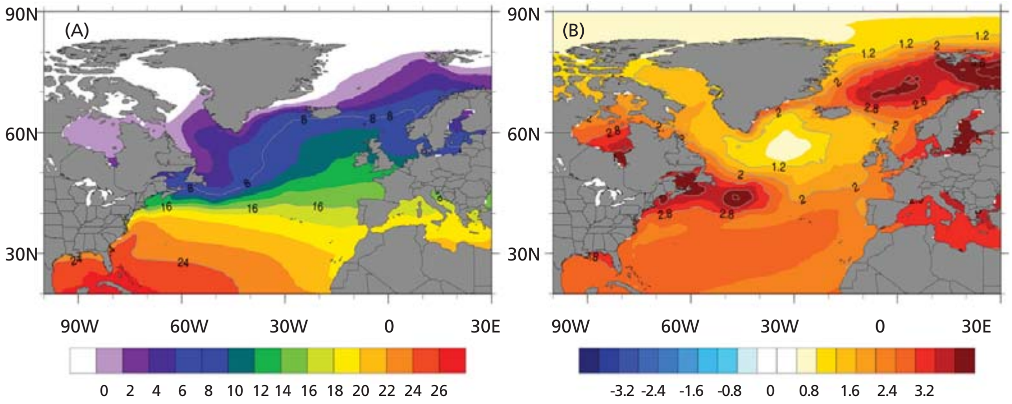
In 2015, the fleet of the Azores (FAO fishing area 27.10) consisted of 761 vessels, 85.5 percent of which had an overall length of 12 metres or less. The most representative species were various tuna species (41.2 percent) which, together with blue jack mackerel (*Trachurus picturatus*), blackspot seabream (*Pagellus bogaraveo*), conger eel (*Conger conger*) and silver scabbard fish (*Lepidopus caudatus*), represented around 66 percent of the total of landings (STECF, 2017).

5.2 OBSERVED AND PROJECTED IMPACTS OF CLIMATE CHANGE ON THE MARINE ENVIRONMENT

5.2.1 Temperature and salinity

FIGURE 5.1

Sea surface temperature (Climate Model Intercomparison Project version 5 [CMIP5] ensemble average, °C) interpolated on a 1×1 grid for the entire year



(A) mean climate from the historical experiment for the period (1956 to 2005); (B) difference in the mean climate in the future time period (RCP8.5: 2050 to 2099) compared to the historical reference period (1956 to 2005).

Sea surface temperatures (SST) in the North Atlantic have generally increased by 0.1 °C to 0.5 °C/decade over the past century, and the rate of warming has been particularly rapid since the 1980s. Warming is expected to continue, as suggested by global models (see Figure 5.1) into the future. From 1982 to 2010, spatial differences were observed in the SST trend across the North Atlantic with the highest rates of warming (well above 0.5 °C per decade) observed for the Gulf Stream front, the subpolar gyre and Labrador Sea on the western margin, and the European continental shelf above 50 °N in the east (Taboada and Anadón, 2012). On the other hand, the mean SST off Eastern Greenland decreased. Isotherms of annual mean SST have generally shifted to higher latitudes at a rate less than 50 km per decade (Taboada and Anadón, 2012). In the future, warming is expected everywhere (Figure 5.1) but particularly in the Atlantic-Arctic, including the Barents Sea and Greenland Sea, as well to the east of the Grand Banks, where SST is anticipated to rise by more than 3 °C over the next 50 to 100 years. By contrast, only moderate warming (less than 1 °C) is anticipated off SW Greenland (Figure 5.1).

In the Northwest Atlantic, the cold Labrador Current meets the warm Gulf Stream off the Grand Banks, southeast of Newfoundland and results in extremely rich fishing grounds. These currents interact with topographical discontinuities such as Cape Cod along the continental shelf to create large differences in the physical and chemical environment of the southern (mid-Atlantic shelf) and northern (Gulf of Maine and Scotian Shelf) components of the region. Within the last 35 years, summertime water temperatures in both southern and northern regions have warmed at approximately 1 °C per decade (Thomas *et al.*, 2017). Some areas such as the Gulf of Maine have changed more markedly and have witnessed changes in the seasonality of "summer" temperatures (earlier onset and increased duration).

Across the Northwest Atlantic, average SST is projected to increase an additional 2.0 °C to 4.0 °C by 2100 under the business as usual (RCP8.5) scenario with a high amount of spatial variability in warming (Figure 5.1). The frequency of storminess is expected to increase and sea level rise is expected to continue, which would negatively impact fishing activities.

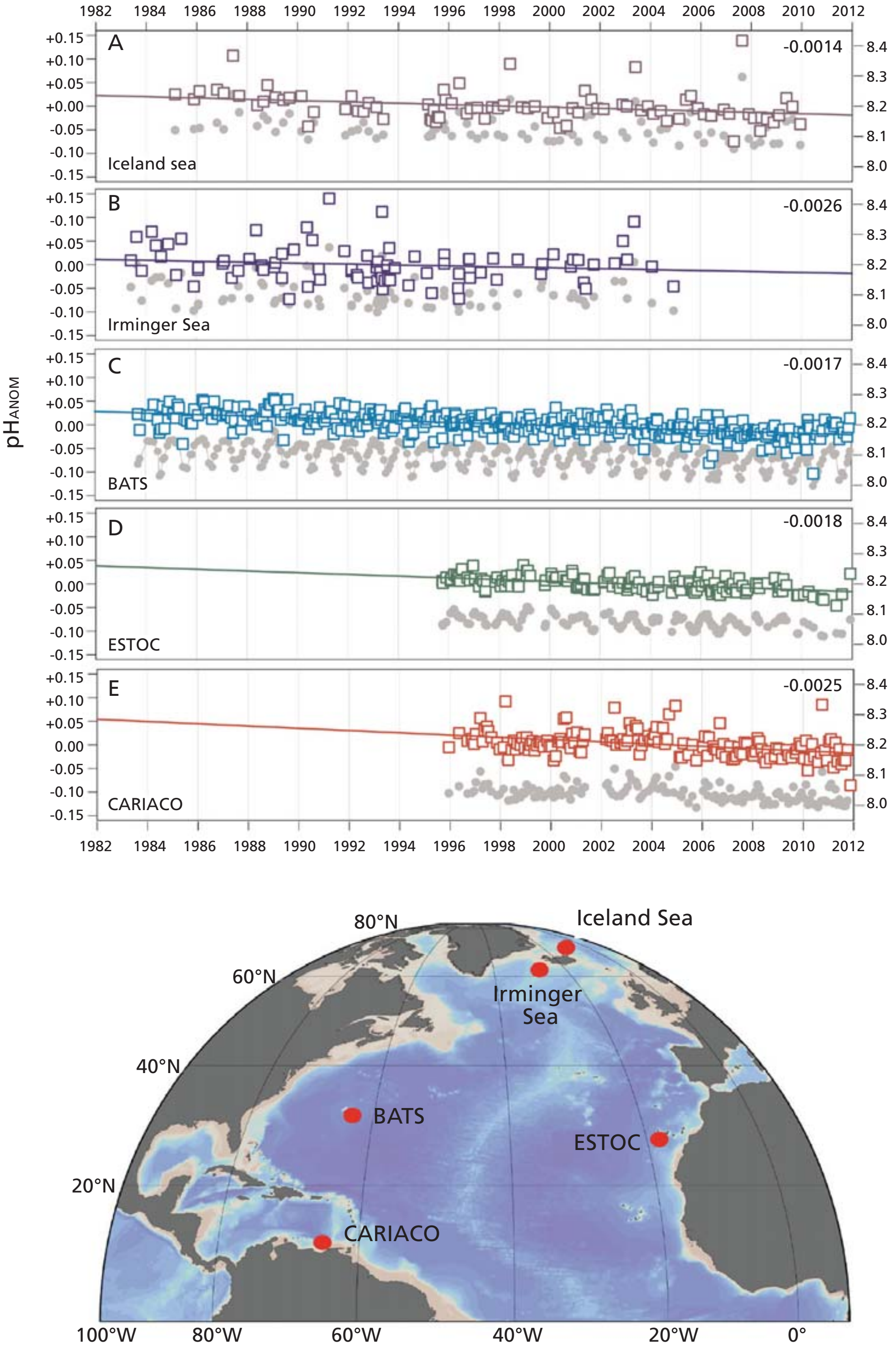
Assessment of trends in water temperature, salinity and acidification in the Atlantic-Arctic region is difficult because of multi-decadal variability and a general lack of historical measurements prior to the 1950s. Seawater temperatures have risen dramatically since the 1970s, and subsurface pulses of relatively warm water of Atlantic origin have been detected all around the Eurasian basin (Rhein *et al.*, 2013). Extreme warming has occurred in the Kara and Barents seas during the winters of 2000 to 2016 (Kohnemann *et al.*, 2017). Singh *et al.* (2013) reported particularly large increases in SST by as much as 4 °C in areas such as the Labrador Sea, the Iceland Sea (along the Greenland coast and near Iceland), the Greenland Sea, and in Hudson Bay between 1982 and 2010. With the observed decline in sea ice and release of freshwater from multi-year sea ice (or the Greenland Ice sheet), water salinity has decreased. In the period from 1992 to 1999, freshening of all regions throughout the Arctic as well as increased freshwater transport out of the Arctic was detected (Dickson *et al.*, 2002).

5.2.2 Carbonate chemistry and ocean acidification

Five, relatively long-term data sets in the North Atlantic show a consistent pattern of decrease in surface-ocean pH (Figure 5.2) albeit with strongly variable site-specific values (e.g. -0.0014 pH units/year in the Iceland Sea; -0.0026 pH units/year in the Irminger Sea) (Bates *et al.*, 2014). These measurements are usually made at 5 m to 20 m water depth and pH and saturation state decrease (and pCO_2 increases) with increasing water depth. Moreover, considerable spatial variability in pCO_2 in shelf waters is caused by the influence of rivers. In the European shelf seas, both observations and modelling show that CO_2 levels in near-surface can vary between 200 ppm and 450 ppm, contributing to a pH variability of as much as 1.0 pH unit over an annual cycle (Provoost *et al.*, 2010). Collated pH measurements from waters around the United Kingdom of Great Britain and Northern Ireland suggest a long-term decline over the past 30 years, and North Sea pH has decreased at a rate of around 0.0035 pH units per year (Ostle *et al.*, 2016).

FIGURE 5.2

North Atlantic time series showing long-term decrease in surface pH at five sites: Iceland Sea, Irminger Sea, Bermuda Atlantic Time-series Study (BATS), European Station for Time series in the Ocean Canary Islands (ESTOC) and Cariaco Basin, Venezuela (CARIACO Ocean Time Series)



Top: site location map; Bottom: data for each site shown as pH anomalies (coloured symbols, left hand scale) and observed pH (grey symbols, right hand scale), the latter calculated from dissolved inorganic carbon and total alkalinity from Bates *et al.* (2014), omitting data from Pacific time series.

Areas of the Northwest Atlantic have witnessed decreases in pH consistent with ocean acidification (OA) but changes in large-scale circulation patterns and runoff from large estuaries have caused larger changes in the saturation state (Ωar) of aragonite, a measure of the degree of OA. Coastal areas near large estuaries and cold-water currents display greater acidification (a lower saturation state of aragonite) compared to deeper, offshore waters of warmer origin (Wanninkhof *et al.*, 2015). The pH of bottom waters of estuaries such as the Gulf of St. Lawrence has decreased 0.2 pH to 0.3 pH units over the last 70 years with expected negative impacts on shellfish (molluscs) and potentially on fish early life stages.

In the Arctic, OA is particularly important because solubility of CO_2 is greater at cold temperatures and, consequently, the onset of under-saturation (Ωar less than 1) will occur first in polar waters. There are very few long-term time series measurements of pH in the Atlantic high Arctic, however, decreases in pH and calcium carbonate concentrations have been observed in the surface waters on the continental shelves along the Arctic coasts, although it is thought that this is mainly a result of freshwater influx from melting ice-caps and rivers emptying into the Arctic Ocean (Steinacher *et al.*, 2009).

5.2.3 Natural climate variability in the North Atlantic

The North Atlantic experiences decadal to annual oscillations in weather patterns that impact the productivity of its marine ecosystems and fish stocks. The Atlantic Multi-decadal Oscillation (AMO) is a quasi-cycle of roughly 70 years of a little more than 1 °C change in SST. The North Atlantic Oscillation (NAO), by contrast, is the difference in atmospheric pressure between the Azores high and the Icelandic low and year-to-year changes in the NAO cause changes in wind speed, precipitation, evaporation, and the exchange of heat between ocean and atmosphere with strong impacts on oceanic conditions. During winters with a strong NAO index, the ocean responds quickly and the effects can continue throughout the following year. Long-term, climate-driven warming is superimposed on natural climate variability such as the AMO and NAO and the ecological consequences of these combined processes are challenging to understand. Although the NAO is one of the climate indices for which it is most difficult to provide accurate future projections (IPCC, 2013), the combined estimates from different climate models suggest that the NAO may become slightly more positive (on average) in the future (Karpechko, 2010).

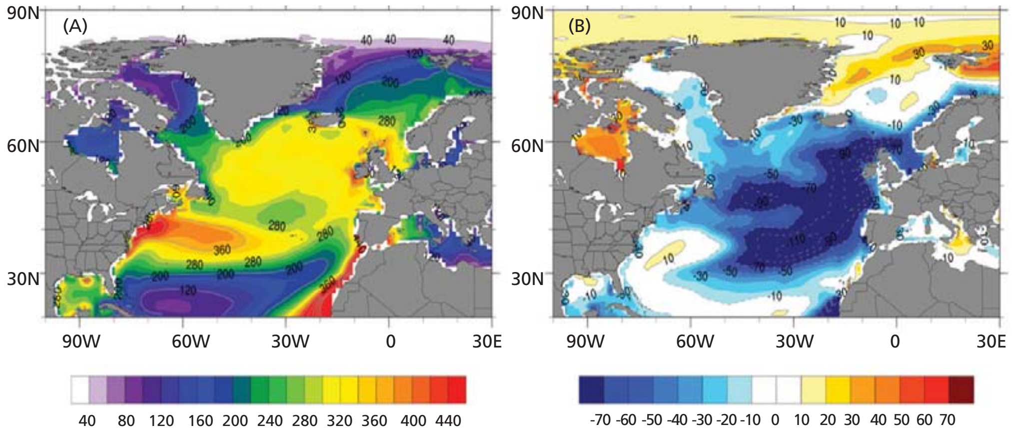
5.2.4 Phytoplankton productivity

A major uncertainty with regard to future projections for fisheries yield (Chapter 4) is the lack of clear consensus as to whether primary production (phytoplankton) will increase or decrease at different localities and, therefore, which countries' fisheries will be "winners" or "losers" in the long-term. At a local scale, recent studies for the Northeast Atlantic (e.g. Fernandes *et al.*, 2017) have tended to use outputs from downscaled regional models that anticipate a decline in net primary production. Consequently, these studies also suggest an overall decline in the net present value of fisheries in most subregions. Global climate models also suggest an overall decline in primary productivity for much of the Northeast Atlantic (see Figure 5.3), but a moderate increase for the Northwest Atlantic (eastern United States of America) and especially the Atlantic-Arctic and in Hudson Bay.

While spring phytoplankton blooms occur in the Arctic Ocean, they are currently constrained by the sea ice and strong vertical stratification. Although the dynamic processes influencing phytoplankton growth such as the extent of cracks (leads) in pack ice are still being resolved, for this Atlantic-Arctic subregion, sea ice is declining and ice-free summers may occur by the mid-twenty-first century. Such change may cause Arctic phytoplankton production to increase and mimic conditions currently experienced in the Northeast Atlantic (Yool, Popova and Coward, 2015). This could, in turn, result in additional fisheries benefits for the Atlantic-Arctic subregion.

FIGURE 5.3

Average, annual primary productivity (CMIP5 ensemble average, 1×10^{-9} mol/m^2/s) interpolated on a 1×1 grid



(A): mean primary organic carbon production by all types of phytoplankton for the period (1956 to 2005). (B): difference in the primary productivity in the future time period (RCP8.5: 2050 to 2099) compared to the historical reference period (1956 to 2005).

5.2.5 Dissolved oxygen

There is evidence that areas of low dissolved oxygen have started to proliferate around the world (Diaz and Rosenberg, 2008). Stendardo and Gruber (2012) examined oxygen trends over five decades in the North Atlantic and identified declines in almost all regions during the period from 1960 to 2009. Whether or not these changes in dissolved oxygen are a result of long-term climate change remains unclear, and it is also unknown whether such changes will impact on commercial fish and their fisheries (Townhill *et al.*, 2017).

5.2.6 Marine ecosystems

Similar to other ocean areas, a mixture of pressures including climate change, overfishing, habitat modification and eutrophication have changed the composition and distribution of marine flora and fauna in the northern Atlantic. Climate change may have important consequences for the base of the food web such as the seasonal timing and magnitude of blooms of phytoplankton and/or zooplankton at high latitudes (e.g. Henson *et al.*, 2017). Global-scale climate modelling of phytoplankton has projected large shifts in the seasonal timing of blooms throughout subpolar waters of the North Atlantic and polar waters of the Arctic (Henson *et al.*, 2017). Zooplankton resources, important to the diets of early life stages of fish, may also drastically shift in the future. For example, *Calanus finmarchicus* is a key species of zooplankton in the diets of early life stages of many commercially important fish on shelf areas throughout much of the North Atlantic. Projected warming of bottom waters of the Northeast shelf of the United States of America under a "business as usual" scenario of greenhouse gas emissions is expected to decrease the average abundance of *C. finmarchicus* in this region by as much as 50 percent by the end of this century (Grieve, Hare and Saba, 2017).

In the Northeast Atlantic, major biogeographical shifts in zooplankton have been identified in response to warming including poleward increases in warm-water species and a reduction in the number of cold-water species in the same areas (Beaugrand, Luczak and Edwards, 2009). All zooplankton assemblages exhibited coherent, long-term shifts but the speed of these biogeographic shifts was surprisingly rapid. Warm-temperate, pseudo-oceanic species experienced a poleward shift of about 10° of latitude (52 to 62 °N, 10 °W) or 23 km per year for the period 1958 to 2005 (Beaugrand, Luczak and Edwards, 2009). The magnitude of the species shifts was, however, similar to the poleward shift of some isotherms. These shifts have caused an increase in the diversity of calanoid copepods in the Northeast Atlantic and its adjacent seas (such as the North Sea).

5.3 CLIMATE CHANGE EFFECTS ON STOCKS SUSTAINING THE MAIN FISHERIES

5.3.1 Distribution and abundance

In the Northwest Atlantic, thorough monitoring of fish stocks within trawl surveys has occurred annually for at least four decades by the US NOAA NMFS and DFO. Additional, broad-scale ecosystem surveys have been conducted within specific decades making the mid-Atlantic Bight, Gulf of Maine and Scotian Shelf a data-rich region. Within US waters, Nye *et al.* (2009) investigated shifts in 36 commercial fish stocks over a 40 year time period from 1968 to 2007. There were clear poleward shifts consistent with warming in many fish stocks, most notably for alewife (*Alosa pseudoharengus*), American shad (*Alosa sapidissima*), silver hake (*Merluccius bilinearis*), red hake (*Urophycis chuss*), and yellowtail flounder. Changes were observed in the minimum and maximum latitude of occurrence of fish stocks and 17 stocks significantly increased their mean depth of occurrence. Shifts in distribution were most closely associated with changes in the AMO that was consistently positive in the late 1990s and 2000s. When data on the distribution of both adult fish and their eggs and larvae were compared between 1977 to 1987 and 1999 to 2008, most taxa (23 of 27) displayed shifts and, in half of those taxa, larvae and adults shifted in the same direction, either poleward and/or deeper (Walsh *et al.*, 2015). In this and other regions, fish are expected to move poleward, if possible, to track the same water temperatures. Across Atlantic waters of the United States of America and Canada (33 °N to 48 °N latitude), projected warming until 2060 is expected to modify the habitats in terms of suitable water temperatures of 76 percent of the fishery target species in Canada (55 percent contract, 21 percent expand) and 85 percent of those in the United States of America (65 percent contract, 20 percent gain) (Shackell, Ricard and Stortini, 2014).

In an analysis of 50 fish species common in the Northeast Atlantic, 70 percent responded to warming by changing distribution and abundance (Simpson *et al.*, 2011). Specifically, warm-water species with smaller maximum body size generally increased in abundance while cold-water, large-bodied species decreased. Fishery-independent survey data indicate that the centres of distribution for a broad range of North Sea fish species have shifted by distances ranging from 48 km to 403 km between the 1970s and early 2000s (Dulvy *et al.*, 2008; Perry *et al.*, 2005). The North Sea demersal fish assemblage has shifted to deeper waters at an average rate of 3.6 m per decade over the last 30 years (Dulvy *et al.*, 2008).

In the North Sea, the locations where peak commercial catches of target species such as cod, haddock, plaice and sole were obtained have all shifted over the past 100 years (Engelhard *et al.*, 2011; Engelhard, Righton and Pinnegar, 2014). However, distributions have shifted in various directions, and shifts cannot simply be described as poleward. Annual groundfish surveys between 1999 and 2007 indicate that warm-water "Lusitanian" fishes (including sole, john dory (*Zeus faber*), sardine (*Sardina pilchardus*) and boarfish (*Capros aper*) have increased on the shelf to the north and west of Ireland, while the "boreal" community (including cod, haddock, plaice and herring) has declined to the south (Lynam, Cusack and Stokes, 2010). Pelagic fish surveys between 1965 and 2012 suggest a strong "subtropicalization" of species in the North Sea and Baltic Sea (Montero-Serra *et al.*, 2015). Pelagic fish communities throughout the Northeast Atlantic have shifted away from cold-water assemblages typically characterized by herring and sprat from the 1960s to 1980s, to warmer-water assemblages typified by mackerel, horse mackerel, sardine and anchovy (*Engraulis encrasicolus*) from the 1990s onwards. In all cases, SST was identified as the primary driver of change (Montero-Serra *et al.*, 2015). A similar shift from a colder to warmer fish community occurred between 2004 and 2012 in the Barents Sea where an Arctic community characterized by bigeye sculpin (*Triglops nybelini*), Greenland halibut, and snailfish (*Liparis* spp.) shifted poleward and was replaced largely by a boreal (Atlantic shallow-water) community dominated by American plaice, Atlantic cod and haddock (Fossheim *et al.*, 2015).

Species may migrate across political or management boundaries, which can create conflict in the allocation of quotas (portions of the overall total allowable catch or TAC) to the different nations sharing the common stock. A recent, notable example arose with regard to quota allocations for mackerel between Norway and the EU, and between Iceland, the Faroe Islands and the EU in the Northeast Atlantic. Starting in 2007, North Sea mackerel began to shift to the north and the west, away from Norway, eventually resulting in disagreements in 2009 over the effective quota, and hence permissible catches, for Norwegian vessels in EU waters. During the same period, with the sudden high abundance of mackerel in their territorial waters, Iceland and the Faroe Islands unilaterally claimed nearly 10-fold increases in their quota for this stock (representing 46 percent of the internationally agreed TAC). Whether the apparent changes in mackerel distribution, northwards and westwards, were a result of long-term climate change remains unclear. Hughes *et al.* (2014) suggested that SST had a significant positive association with the observed shift of mackerel and historical movements of mackerel to the western North Sea and off the coast of Iceland also coincided with positive (warm) phases of the AMO (Beare *et al.*, 2004).

MacKenzie *et al.* (2014) reported that commercial boats targeting mackerel in waters east of Greenland have now started catching bluefin tuna (*Thunnus thunnus*). The presence of bluefin tuna in this area of the North Atlantic is likely as a result of a combination of warmer temperatures and immigration of an important prey species (mackerel). Since 2008, ICCAT has granted a small but increasing share of bluefin tuna quota to Norway and Iceland. ICCAT has also amended its criteria for allocating quota shares to recognize shifts in species distribution, such that they are not only based on a "track record" of fishing but also the rights of coastal states to make use of resources present within their EEZ (TemaNord, 2011).

Models such as those described in Chapter 4 project that the distributions of exploited species will continue to shift in the next five decades both globally and in the Northeast Atlantic specifically (Cheung *et al.*, 2010; Lindegren *et al.*, 2010). Uncertainty in projected warming among different global climate models notwithstanding, the combined estimates from three species distribution models for 14 commercial fish in the Northeast Atlantic suggested poleward shifts at an average rate of 27 km per decade (Jones *et al.*, 2013), which is slightly faster than that (20 km per decade) currently observed for common fish in the North Sea (Dulvy *et al.*, 2008). Applying a similar model to predict the distribution of eight Northeast Atlantic fish species, Lenoir, Beaugrand and Lecuyer (2011) projected an increased probability of occurrence of horse mackerel and anchovy in northern waters in the 2090s compared with the 1960s, a decrease in pollack (*Pollachius pollachius*), haddock and saithe (*Pollachius virens*), and no overall change in the distribution of turbot (*Scophthalmus maximus*) and European sprat.

5.3.2 Changes in fisheries productivity - environmental influences on recruitment

Fishers and scientists in the North Atlantic have known for over 100 years that the status of fish stocks can be greatly influenced by climatic conditions (Hjort, 1914). The amount of young fish entering the fishery each year (recruitment) is critically dependent on the match or mismatch between the occurrence of the larvae and availability of their zooplankton food (Cushing, 1982) as well as a number of other processes such as predation that affect early life-history stages (see Kjesbu *et al.*, 2014; Petitgas *et al.*, 2012). Based on empirical data, there are often strong relationships between recruitment success, fisheries catches and climatic variables as demonstrated, for example, for cod (Planque and Frédou, 1999) and mackerel (Jansen and Gislason, 2011). In widely-distributed species, climate change is expected to have either positive or negative impacts on productivity depending on the geographical location of specific stocks. For example, relationships between recruitment and water temperature of cod stocks across the North Atlantic (Planque and Frédou, 1999) suggest that stocks at the high latitudinal limit (e.g. in the Barents Sea) or the western Atlantic (e.g. Labrador) will benefit from warming, whereas increased water temperature may lead to a collapse of warmer-water cod stocks in the North, Celtic and Irish Seas (Drinkwater, 2005). During recent decades of reduced fishing mortality on cod stocks in the Northeast Atlantic, the stock in the Barents Sea has increased to record levels (spawning stock biomass 2.7 million tonnes in 2013) whereas stocks have been very slow to recover elsewhere.

A clear seasonal shift to earlier appearance of fish larvae has been described for several species in the southern North Sea (Greve *et al.*, 2005), and this has been linked to marked changes in zooplankton composition and sea surface temperature of this region. The loss of a key prey item for cod larvae (the copepod *Calanus finmarchicus*) has been correlated with recent failures in cod recruitment in the North Sea and an apparent increase in flatfish recruitment (Beaugrand *et al.*, 2003). Using market sampling data, Fincham, Rijnsdorp and Engelhard (2013) reported that four out of seven sole stocks had exhibited a significant, long-term trend towards earlier spawning at a rate of 1.5 weeks per decade since 1970. Similarly, the timing of peak roe landings for Atlantic cod in the northern North Sea, central North Sea and Irish Sea occurred 0.9 to 2.4 weeks earlier per decade across three decades. The peak timing was negatively correlated with temperatures experienced by cod during early vitellogenesis, suggesting that rising sea temperatures have contributed to a shift in spawning phenology (McQueen and Marshall, 2017).

5.3.3 Ocean acidification

The impacts of OA are suggested to be most apparent for animals with calcium carbonate shells and skeletons such as molluscs and some crustaceans (Hendriks, Duarte and Álvarez, 2010; Kroeker *et al.*, 2013), but responses are highly variable among and within taxonomic groups. Several major programmes of research are underway in Europe and North America to determine the possible consequences of future OA. In laboratory studies, significant effects have been noted for several important commercial shellfish species, notably mussels, oysters, lobster and Nephrops (e.g. Agnalt *et al.*; Styf, Nisson Sköld and Eriksson, 2013).

Narita and Rehdanz (2017) performed a Europe-wide assessment of the economic impact of OA on mollusc production using two scenarios of biological sensitivity based on a quantitative comparison of findings from previous OA laboratory experiments (Kroeker *et al.*, 2013). Their approach suggested that the highest overall impact was expected in countries with the largest current production such as France, Italy and Spain. For Europe as a whole, the annual impact was estimated to be over 1 billion USD by 2100 although subject to considerable uncertainty.

The impacts of OA on North Atlantic commercial finfish populations is particularly poorly understood. Although several studies have noted that early life stages (eggs and young larvae) may be sensitive to the direct effect of OA (e.g. Franke and Clemmesen, 2011; Frommel *et al.*, 2012), the results appear to depend on the species and habitat of the stock (e.g. Pimentel *et al.*, 2016). Negative impacts of OA on larval growth, development, metabolism and survival have been documented, as have positive, indirect food web impacts of OA on survival and growth (Sswat *et al.*, 2017).

5.4 OTHER NON-CLIMATE STRESSORS (E.G. OVERFISHING, POLLUTION, HABITAT MODIFICATION)

In the 1980s and 1990s many stocks in the Northwest and Northeast Atlantic were overfished. Since 2001, fisheries management in the United States of America, Canada and northern Europe has seen successes in rebuilding stocks. For example, the United States of America currently lists 23 stocks in Atlantic waters as rebuilt including several gadoids, flounders, elasmobranchs, scallop (*Placopecten megallanticus*), monkfish and several highly migratory species. Notably, although once supporting the largest fishery in the Northwest Atlantic, cod stocks collapsed in the 1990s as a result of a combination of both overfishing and warming-driven declines in productivity (Fogarty *et al.*, 2008) and have still not recovered to within safe biological limits despite drastic reductions in fishing effort including complete moratoriums. The collapse of the cod stocks off eastern Canada was followed by historically unprecedented increases in catches of American lobster as well as increases in snow crab and shrimp (*Pandalus borealis*). Large increases and subsequent decreases were also observed in stocks of forage fish. These shifts highlight how whole ecosystems can be restructured by the combined effects of fishing and climate variability and the decades of time required for them to potentially return to previous conditions (Frank *et al.*, 2011).

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, Hjermann and Stenseth, 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 the case of cod in the North Sea, climate-driven warming has been estimated to have been eroding the maximum sustainable yield at a rate of 32 000 tonnes 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 (Cook and Heath 2005).

Engelhard *et al.* (2011) suggest that, apart from climate and fishing, other factors may also have had an important influence on flatfish distributions in the North Sea throughout the twentieth century. These may have included habitat modification, changes in prey availability, and changes in precipitation and run-off patterns. The Dutch and Belgian coasts were previously very good nursery grounds for juvenile plaice, but the closure of the Zuiderzee in the early 1930s and modification of the Rhine, Meuse, and Scheldt estuaries in the 1960s and 1970s have likely reduced the recruitment from these nursery grounds and hence may have affected the abundance and distribution of older age groups in the North Sea.

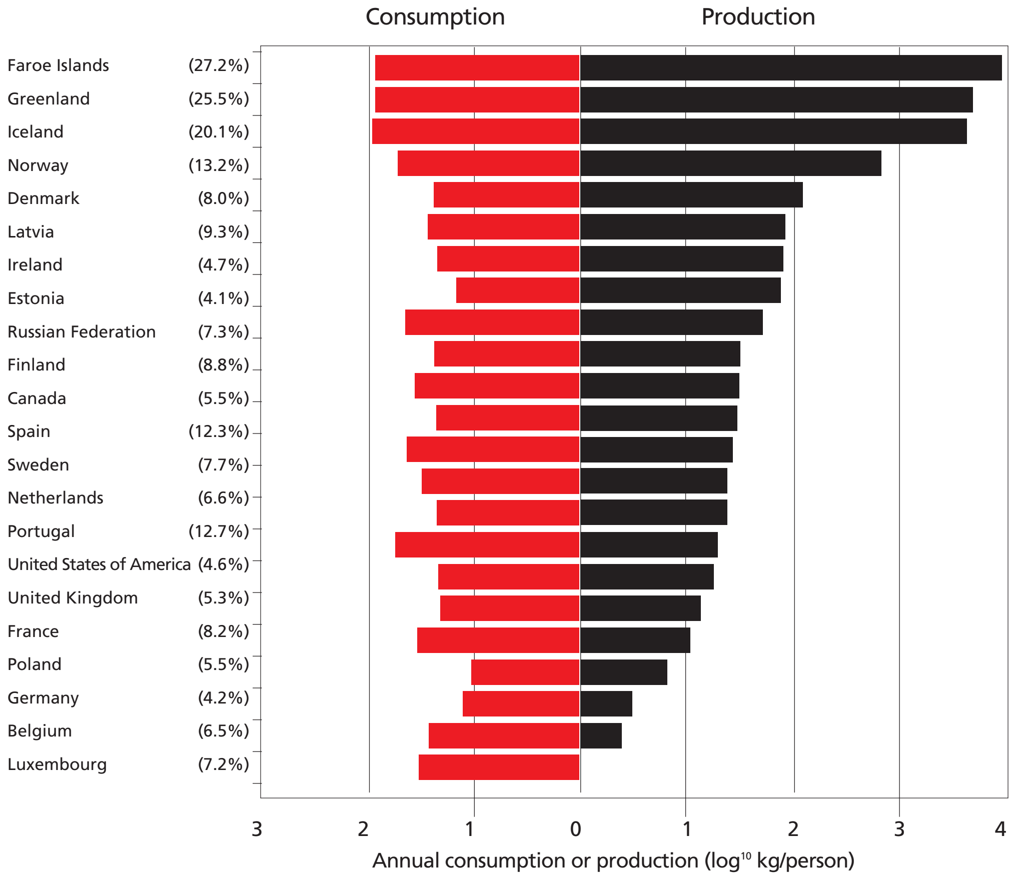
5.5 IMPLICATIONS FOR FOOD SECURITY, LIVELIHOODS AND ECONOMIC DEVELOPMENT

5.5.1 Dependency on fisheries

For most countries bordering the North Atlantic, fisheries contribute very little to national GDP and fish protein constitutes a small proportion of protein intake (see Figure 5.4), hence, fisheries are not primarily concerned with maintaining food or income-security. Some exceptions to this include Greenland, Iceland and the Faroe Islands where fishing remains vital to the national economy and annual per capita consumption of fish and seafood exceeds 80 kg/person. Figure 5.4 shows per capita seafood consumption and production based on FAO data for 2013. Notably, in many northern countries production greatly exceeds consumption, whereas in countries further south, often with large human populations (e.g. Portugal, France, Germany, Belgium, United Kingdom of Great Britain and Northern Ireland), as well as land-locked countries of Europe (e.g. Luxembourg), consumption exceeds production and the deficit is made up via imports from elsewhere.

FIGURE 5.4

Per capita seafood production and consumption in North Atlantic countries based on FAO data for 2013



Number on the Y-axis is the percentage that fish and seafood contributes to total protein consumption in each country.

In specific communities, towns and regions throughout Europe and North America, fishing provides the mainstay of employment. For example, 82 percent of regional activity has been attributed to the fisheries sector in Killybegs (County Donegal) in Ireland (Macfadyen *et al.*, 2010). In the United States of America, communities such as Lubec in Northern Maine or New Bedford in Massachusetts, have few other types of employment available and, hence, are highly dependent on fishing (see Colburn *et al.*, 2016). Natale *et al.* (2013) set out to identify the most fisheries-dependent communities in EU coastal areas. These authors identified 388 fisheries-dependent communities that together play host to 54 percent of total fishery employment in Europe. These included Castlebay and Ullapool in the United Kingdom of Great Britain and Northern Ireland, Hvide Sande and Østerby in Denmark, Puerto de Cillero in Spain, Grundsund in Sweden and Kihnu, Lehtma and Manija in Estonia with a fisheries employment dependency ratio higher than five percent.

Arnason (2007) used an economic model to understand potential economic impacts of climate change on fisheries and on the national economies in Iceland and Greenland. In Iceland, future dramatic increases assumed in fisheries yields resulted in only a minor increase in national GDP (four percent by 2054) even though fishing accounts for approximately ten percent of GDP and 40 percent of export earnings. Given the uncertainty in this analysis, this small increase is close to the margin of error. Benefits for the national economy of Greenland, in which fishing represents 90 percent of the exports, were greater (a 40 percent increase in GDP by 2054) but this assumed an enormous increase in fish production (by 200 percent over 50 years). For other North Atlantic countries with less economic reliance on fisheries, it seems highly unlikely that climate change, as manifested through impacts on fisheries, will have a significant impact on national economic development.

The traditional harvesting techniques of several groups of indigenous peoples in the North Atlantic and Atlantic-Arctic such as the Inuit in Greenland and Canada, Evenk and Nenets in the Russian Federation, and the Saami in Norway and the Russian Federation, are expected to be impacted by climate change. These impacts will result from changes in the composition and productivity of fish stocks as well as changes in sea ice conditions and severe weather (Koivurova *et al.*, 2008). Coastal indigenous peoples are commonly highly vulnerable to ecosystem and economic change. Cisneros-Montemayor *et al.* (2016) attempted to quantify seafood consumption among 1 900 coastal indigenous communities around the world and this included several in the Atlantic-Arctic. Indigenous peoples inhabiting Arctic coasts have the highest mean per capita fish consumption by climate region, at 74 kg per year and these include the Saami, Inuit in Canada (e.g. Inuvialuit around Hudson Bay) and Kalaallit in Greenland.

5.5.2 Maximum catch potential and economic development

Cheung *et al.* (2010) estimated future changes in maximum potential catch (a proxy for maximum sustainable yield) given projected shifts in the distribution of 1 066 species of exploited marine fish and invertebrates from 2005 to 2055 as a result of climate change and changes in marine primary productivity. That study suggested that climate change may lead to large-scale redistribution of global maximum catch potential, with an average of 30 percent to 70 percent increase in yield of high-latitude regions (north of 50 °N in the northern hemisphere), but a drop of up to 40 percent in the tropics. EEZ regions with the highest forecast increases in catch potential by 2055 included Norway and Greenland (and also the Grand Banks of Canada). Areas south of around 50° latitude in the North Atlantic were projected to generally lose out (Cheung *et al.*, 2010). In Chapter 4, similar projections of maximum catch potential are provided based on outputs from a slightly modified version of the same bioclimate envelope model (DBEM) but identical climate forcing data, and also a size-structured ecosystem model (Blanchard *et al.*, 2012). Notably, catches in EEZs of most temperate Northeast Atlantic countries were projected to decline substantially (by approximately 30 percent), in contrast to high latitude regions in the North Atlantic where catch potentials are projected to increase substantially. Shackell, Ricard and Stortini (2014) suggest that stocks are expected to decline in United States of America Atlantic waters and increase in Canadian waters, a trend primarily driven by increases in lobster in Canadian waters.

In the Arctic, total fisheries catch and revenue (or value of fish landed) are projected to increase by about 39 percent (14 percent to 59 percent) by 2050 relative to 2000 according to a study conducted by Lam *et al.* (2014). In that study, catches by European countries (Faroe Islands, Greenland, Iceland, Norway, the Russian Federation and

Sweden) were projected to increase by 20 percent. Projections of increases in revenue, fishers' income, fishing cost, household incomes and economy-wide impacts followed a very similar pattern to catch projections.

Much of the existing literature on the impact of climate change on fisheries economics has been focused on regional and local studies. Eide and Heen (2002) explored the effects of global warming on Barents Sea fisheries and therefore implications for the north Norwegian economy, within which the fisheries sector contributes eight percent to both regional products and employment. A range of possible environmental scenarios was examined including eight different management regimes and four environmental scenarios. The management regimes included open access (or no management), limited entry, quota regulation and combinations of the last two. An increase in average sea temperature of 2 °C resulted in enhanced growth and recruitment of cod and herring, increased annual catches, increased local employment and profitability in these Barents Sea fisheries. Annual catches were however, overwhelmingly determined by the various management regimes tested rather than the different climatic scenarios (Eide and Heen, 2002).

Fernandes *et al.* (2017) used observational and experimental data, theoretical, and modelling approaches to quantify potential effects of ocean warming and acidification on the fisheries catches, resulting revenues and employment in the United Kingdom of Great Britain and Northern Ireland under different greenhouse gas emission scenarios. Standing stock biomasses were projected to decrease significantly by 2050 and the main driver of this decrease was sea surface temperature rise. Overall, losses in revenue were estimated to range between one percent and 21 percent in the short-term (2020 to 2050). Losses in total employment (fisheries and associated industries) may reach approximately three to 20 percent during 2020 to 2050 with the small vessel (less than 10 m) fleet and associated industries bearing most of the losses. Climate change impacts on fisheries profits have been examined in the sardine fishery of the Iberian Atlantic (Garza-Gil, Torralba-Cano and Varela-Lafuente, 2010) and ranged from to non-significant for the Bay of Biscay to positive on the Portuguese coast, where most of the "immigrant" fish species examined are considered marketable (Vinagre *et al.*, 2011).

5.6 VULNERABILITY OF THE MAIN FISHERIES AND THE DEPENDENT COMMUNITIES/ECONOMIES

A number of fishery vulnerability assessments have been conducted for the North Atlantic and many more are currently underway. Some of these studies only focus on the perceived vulnerability of species, whereas others focus on "downstream" vulnerability of fishing fleets and dependent communities.

Hare *et al.* (2016) conducted a climate vulnerability assessment on 82 fish and invertebrate species in the northeast shelf of the United States of America. The authors defined climate vulnerability as the extent to which abundance or productivity of the species could be impacted by climate change and/or decadal variability using life history traits and habitat preferences to rank species in terms of "sensitivity". That study found that overall climate vulnerability is high to very high for approximately half the species assessed; diadromous and benthic invertebrate species (most notably Atlantic salmon *Salmo salar* and Bay scallop *Argopecten irradians*) exhibit the greatest vulnerability. In addition, most species included in the assessment had a high potential for a change in distribution in response to projected changes in climate. Negative effects of climate change were expected for approximately half of the species assessed, but some species were expected to be positively affected (e.g. to increase in productivity and abundance).

Colburn *et al.* (2016) used the ranking of species' vulnerability developed by Hare *et al.* (2016) to determine the most vulnerable fishing communities along the Eastern and Gulf coasts of the United States of America, based not only on catch composition but also on social indicators including employment in the sector, labour force structure and rates of unemployment. Community social vulnerability indices (CVIs) were calculated for 2 659 communities in 19 states from Maine to Texas, of which 1 130 communities showed evidence of commercial and/or recreational fishing activity (Jepson and Colburn, 2013). CVIs were based around "fishing dependence" (a combination of commercial engagement and reliance) and "social vulnerability" (poverty, labour force disruption, personal disruption, housing characteristics). Communities in Massachusetts (e.g. New Bedford) were identified as being particularly vulnerable to climate change because they are highly reliant upon commercial fishing, they exhibit limited catch diversity, they scored poorly on two of the four social vulnerability indicators and highly on two of the three climate change exposure indicators. Several communities in New Jersey (e.g. Barnegat Light) were identified as being particularly vulnerable for similar reasons.

As part of the analyses by Colburn *et al.* (2016), coastal fishing communities vulnerable to sea level rise were also identified. Mid-Atlantic communities in the low lying coastal plain, especially those clustered around the Chesapeake Bay area and the New Jersey shore ranked highly with regard to expected vulnerability to sea level rise. New England communities in the Gulf of Maine and southern parts of the region were not projected to be as vulnerable. South Atlantic communities (North Carolina to Florida's east coast) had pockets of high vulnerability and those in southeastern Florida had the highest concentration of vulnerable communities, including those located in the Florida Keys.

Ekstrom *et al.* (2015) examined US communities most vulnerable to losses in shellfish (mollusc) production as a result of ongoing OA. Their study suggested that 16 out of 23 bioregions around the United States of America are exposed to rapid OA. The marine ecosystems and shelled molluscs around the Pacific Northwest are expected to be exposed soonest to rising global OA, followed by those on the Gulf of Maine and Atlantic coast of the United States of America. Communities highly reliant on shelled molluscs in these bioregions are at risk from OA either now or in the coming decades. Pockets of marine ecosystems along the East and Gulf coasts will experience acidification earlier than global projections indicate, because of the presence of local amplifiers such as coastal eutrophication and river discharge of water with low saturation state (Ωar). The areas that will be exposed to OA (including local amplifiers) and where high and medium–high social vulnerability is present include southern Massachusetts, Rhode Island, Connecticut, New Jersey, portions around the Chesapeake Bay, and the Carolinas.

5.7 RESPONSES (ADAPTATION)

Climate change is affecting marine and coastal ecosystems throughout the North Atlantic, including commercial, recreational and subsistence fisheries. Traditional fisheries management tools, such as restrictions on allowable catch, landing size, seasonal closures, gear restrictions, marine protected areas, essential fish habitat protection, and protection of spawning aggregations, are and will remain necessary (see Grafton, 2010) but may not be sufficient on their own to sustain fisheries in the face of the combined onslaught of climatic and non-climatic stressors in the future.

A wide diversity of adaptation measures has been tested, applied and advocated in the North Atlantic and these are reviewed in two reports from the United States of America (Gregg *et al.*, 2016) and the United Kingdom of Great Britain and Northern Ireland (Defra, 2013). Climate adaptation actions are taken to either avoid (or minimize) or take advantage of climate change impacts, either by decreasing vulnerability or increasing resilience. In the United States of America, the EcoAdapt program aims to promote adaptation action in the fisheries sector by: 1) providing real-life, practical adaptation case studies to catalyse creative thinking, and 2) synthesize information collected through interviews and surveys to further develop the field of study. Gregg *et al.* (2016) provides a summary of adaptation actions in the United States of America (both Atlantic and Pacific), based on interviews with federal, tribal, state and other practitioners. Commonly used adaptation approaches and examples are presented in four broad categories:

1. **Capacity building:** strategies include conducting research and assessments, investing in training and outreach efforts, developing new tools and resources, and monitoring climate change impacts and adaptation effectiveness.
2. **Policy:** strategies include developing adaptation plans, creating new or enhancing existing policies, and developing adaptive management strategies.
3. **Natural resource management and conservation:** strategies include incorporating climate change into restoration efforts, enhancing connectivity, reducing local change, and reducing non-climate stressors that may exacerbate the effects of climate change.
4. **Infrastructure, planning, and development:** strategies include protecting critical coastal infrastructure used by the fishing industry, and creating or modifying coastal development measures (e.g. removing shoreline hardening, encouraging low-impact development) to increase habitat resilience.

The majority of fishery adaptation efforts in the United States of America to date have been focused on capacity building, including conducting research and assessments, creating resources and tools, and monitoring how climatic changes are affecting species, habitats, and fishing communities (Gregg *et al.*, 2016). However, EcoAdapt recommends the following "best bets" for advancing climate-informed fisheries management over the long term (see Gregg *et al.*, 2016):

1. **Advance monitoring efforts of climate-driven impacts on species, habitat, and fishing communities.** Documenting environmental and climatic change is key to natural resources management.
2. **Enhance habitat connectivity and areas under protection.**
3. **Reduce non-climate stressors.** The cumulative effects of non-climate stressors reduce the overall resilience of species, habitats and communities to climate change.
4. **Create flexible multi-species permitting, licensing and management plans.** Enabling flexibility in terms of when, where, what and how much is harvested will become increasingly important to sustain fishing livelihoods.
5. **Adjust quotas to help sustain stocks** (e.g. reduce fishing pressure on vulnerable stocks).
6. **Temporarily close fisheries if necessary.** Given the uncertainty of climate change and the risks associated with extreme events, managers should adjust status quo policies by supporting rapid response measures to reduce stress on vulnerable stocks, including temporary closures.
7. **Evaluate potential and establish procedures for new commercial and recreational fisheries** (e.g. establishment of catch limits, new permitting procedures).
8. **Create international cooperative fisheries agreements.** Climate change will not be confined by political or social boundaries.
9. **Diversify fisheries and/or livelihoods.** In some areas, climate-induced effects on fisheries may threaten entire communities' livelihoods.

In 2013 the United Kingdom of Great Britain and Northern Ireland Department for Environment Food and Rural Affairs (Defra) commissioned its *Economics of Climate Resilience* (ECR) report on "sea fisheries" (Defra, 2013), which included a detailed assessment of whether or not the United Kingdom of Great Britain and Northern Ireland fishing sector will be able to adapt to the opportunities and threats associated with future climate change. Against the background of current policy, the adaptive capacity of the United Kingdom of Great Britain and Northern Ireland fishing industry as a whole was judged to be relatively high. This is because it has strong commercial incentives to make the most of profitable opportunities, and fishing vessel operators are used to dealing with constantly changing weather and fish stock sizes. However, the ability of some segments within the sector (e.g. small vessel operators) to adapt is likely to be more constrained than others. 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 highlighted for the United Kingdom of Great Britain and Northern Ireland fishing industry as a whole included:

1. Travelling further to fish for current species, if stocks move away from United Kingdom of Great Britain and Northern Ireland ports, particularly for large pelagic fishing vessels, such as those targeting mackerel and herring.
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. Enhancing vessel capacity if stocks of currently fished species increase and sufficient quota allows.
4. Changing gear to fish for different species, if new or more profitable opportunities to fish different species are available, especially if these are not yet covered by EU quota restrictions (e.g. squid).
5. Developing routes to export markets to match the changes in catch supplied. These routes may be to locations (such as southern Europe) that currently eat the fish stocks that may move into the United Kingdom of Great Britain and Northern Ireland EEZ.
6. Stimulating domestic demand for a broader range of species, through joint retailer and media campaigns.

Kopke and O’Mahony (2011) provided an overview of adaptive capacity, barriers to adaptation, and information needs in the Irish fisheries sector, which echoed many of the “barriers to adaptation” cited in the ECR report (Defra, 2013). Barriers included “market failures” stemming from uncertainty around new or emerging species in the United Kingdom of Great Britain and Northern Ireland EEZ. “Information barriers” include that not all vessel operators may be aware of best practice techniques used by foreign fleets that can allow them to maximize opportunities offered by shifts in stock distribution. “Policy barriers” exist because the process of collecting and considering scientific evidence required to change regulations for setting sustainable catch quotas is likely slower than the pace of changes in stocks. There is a risk that quota allocations significantly restrict fishing activity where stocks are increasing and in some circumstances incentivize maladaptation. “Behavioural constraints” stem from the relatively limited number of fish species favoured by United Kingdom of Great Britain and Northern Ireland consumers. Although emerging species can be sold to niche markets and restaurants, for the most part, such species are exported.

The ECR report identified that fisheries management and quota arrangements can severely constrain the ability of fishers to adapt to climate change and this is true on both sides of the Atlantic. For example, under the EU Common Fisheries Policy, TACs are shared between EU member nations through pre-agreed “relative stability” arrangements. These arrangements are based on member state catches during a historical reference period, 1973 to 1978 (Morin, 2000) and give each member state a fixed percentage share of the total stock in perpetuity. Climate change has since shifted the geographical distribution of commercial species so that the national shares no longer coincide with geographic proximity. Small amounts of quota can be swapped each year between member states which could theoretically be used if distributions of managed stocks shift into new areas, or retreat from traditional ones. Some sharing arrangements (“fisheries agreements”) are also in place between the EU and non-EU countries (such as Norway, Iceland, Greenland and the Faroe Islands) for stocks that are shared (e.g. mackerel and cod). Climate change greatly complicates the situation, as demonstrated during the recent North Atlantic “mackerel wars” (see Section 4.1 above).

Governments have implemented various measures to manage fisheries, both to conserve fish stocks and to help communities that depend on fishery resources to adapt to changes caused by overfishing and other factors. Measures include buybacks, introduction of transferable quotas, and investments in alternative sources of employment and income. Successful adaptation to climate change is likely to involve an extension of such policies, and in Europe the annual cost of adaptation has been estimated to range between USD 0.03 billion and USD 0.15 billion (World Bank, 2010). As countries surrounding the North Atlantic are some of the most affluent on the planet, it is assumed that, for the most part, "adaptive capacity" is high and that this will reduce long-term, overall vulnerability compared to other FAO regions.

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This FAO Technical Paper is aimed primarily at policymakers, fisheries managers and practitioners and has been prepared particularly with a view to assisting countries in the development of their Nationally Determined Contributions (NDCs) to the Paris Climate Agreement, the next versions of which are to be submitted by 2020. The Technical Paper provides the most up-to-date synthesis on the impacts and risks of, and the opportunities and responses to climate change in the fisheries and aquaculture sector, in the context of poverty alleviation.

It covers marine capture fisheries and their environments (Chapters 4 to 17), inland waters and their fisheries (Chapters 18, 19 and 26), as well as aquaculture (Chapters 20 to 22). The Technical Paper also includes chapters on disasters and extreme events (Chapter 23) and health and food safety hazards (Chapter 24). Guidance and tools are presented for planning and implementing effective and explicit adaptation (Chapter 25), while taking into consideration the impacts on fisheries and aquaculture of potential adaptations to climate change in other sectors (Chapter 26). Mitigation is addressed in Chapter 27, which provides quantitative information on the fisheries and aquaculture sector's contributions to greenhouse gas emissions, as well as strategies and tools for mitigation.

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