Chapter 3

Pan-Arctic Fisheries and their Assessment

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Additional information is available at the end of the chapter

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Abstract

Pan-Arctic fisheries are highly diverse in their purpose, species biology, productivity, economic and strategic importance as well as in how they are prosecuted. They range from full industrial fisheries to community-based artisanal, sport and subsistence fisheries. The nature of Arctic ecosystems in the region varies from extremely productive to relatively barren in terms of fisheries production. Gear types vary, but offshore trawl fisheries and inshore and freshwater gillnet fisheries are the most common. Rights-based fisheries (e.g., for indigenous inhabitants) are more prominent in the Canadian and American Arctic than in European jurisdictions. The principal harvested species in freshwater environments tend to be from few taxa mainly *Salvelinus* spp. and from the family *Coregonidae, w*hile the marine taxa are more diverse. Compared to north temperate fisheries, Arctic fisheries have impressive variation across longitudes; some jurisdictions support only small-scale subsistence fisheries, whereas others contain some of the largest yields among industrial fisheries. Approaches to scientific assessment are also highly diverse with a range from catch-based indicators to sophisticated fully age-structured population models.

Keywords: arctic, fisheries, models

1. Introduction

This chapter describes some of the major Pan-Arctic fisheries, the stock assessment methods applied to assess them and how the fisheries might change with climate warming and further development of the northern regions. The chapter is a broad overview to introduce the reader to this topic which has not been included in most fisheries text books.

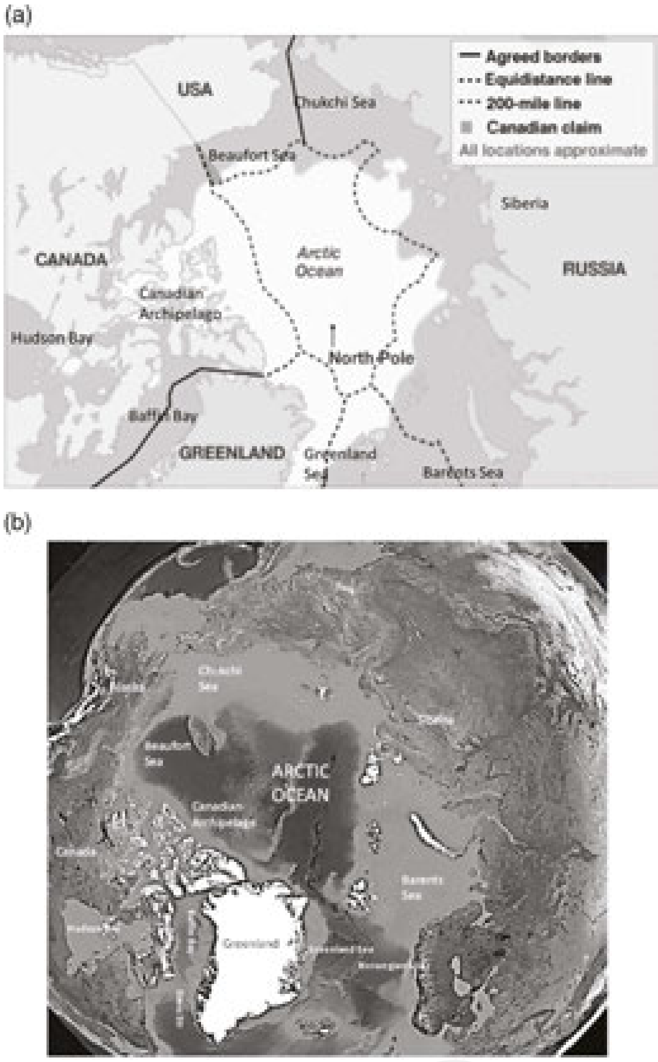

Figure 1. (a) Arctic Ocean and surrounding land masses showing approximate jurisdictional boundaries and (b) fishing areas discussed in the text.

Pan-Arctic fisheries are highly diverse in their purpose, species biology, productivity, economic and strategic importance as well as in how they are conducted. They range from full industrial fisheries to community-based artisanal, sport and subsistence fisheries. Rights-based fisheries (e.g., for indigenous inhabitants) are more prominent in the Canadian and American Arctic than in European jurisdictions. The patchy nature of Arctic environments has a strong influence on species life cycles such that geographically extensive migrations between critical habitats for rearing and growth, spawning or calving and over-wintering are undertaken by many taxa. Species tend to be long-lived. The principal harvested species in freshwater environments tend to be from few taxa mainly *Salvelinus* spp. and from the family *Coregonidae*. While the marine taxa are more diverse, the dominance of marine mammals at the apex

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of the food chain and as a source of food for humans is important in driving fisheries policy for a large portion of the Arctic zone. Compared to north temperate fisheries, Arctic fisheries have impressive variation across longitudes; some jurisdictions support only small-scale subsistence fisheries, whereas others contain some of the largest yields among industrial fisheries.

The chapter is organized by geographic regions: Barents Sea, Arctic Atlantic–Norwegian Sea, Arctic Atlantic–Greenland Sea, Greenland–continental, Baffin Bay–Davis Strait, Hudson Bay, Canadian Archipelago, Canadian Arctic mainland, Alaska, Beaufort Sea, Siberia and Chukchi Sea (**Figure 1**).

2. Barents Sea

The Barents Sea (**Figure 2**) is on the continental shelf surrounding the Arctic Ocean. It connects with the Norwegian Sea to the west and the Arctic Ocean to the north and the Kara Sea to the east. Its contours are delineated by the continental slope between Norway and Spitsbergen to the west, the top of the continental slope towards the Arctic Ocean to the north, Novaya Zemlya archipelago to the east and the coasts of both Norway and Russia to the south. It covers an area of approximately 1.4 million km^2, has an average depth of approximately 230 m has and a maximum depth of about 500 m at the western end of Bear Island Trough. Its topography is characterized by troughs and basins (300–500 m deep), separated by shallow bank areas, with depths ranging from 100 to 200 m. The three largest banks are Central Bank, Great Bank and Spitsbergen Bank. Several troughs over 300 m deep run from central Barents Sea to the northern

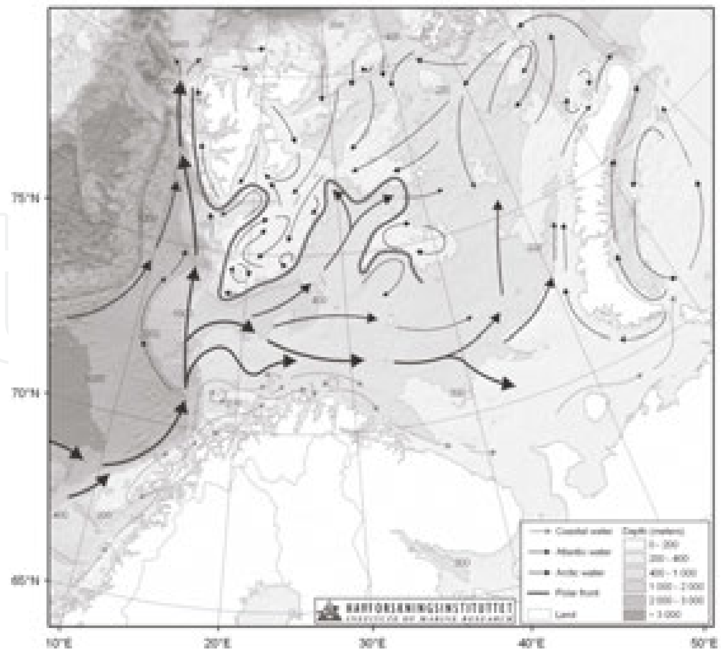

Figure 2. The main features of the circulation and bathymetry of the Barents Sea [2].

(e.g., Franz Victoria Trough) and western (e.g., Bear Island Trough) continental shelf break. These western troughs allow the influx of Atlantic waters to the central Barents Sea. The Barents Sea is shared between Russia and Norway, and there is long history of relatively successful cooperation in fisheries management, even during periods that were otherwise marked by political tensions [1].

The Barents Sea is home to the most productive commercial fisheries in the Pan-Arctic Region (**Figure 2**).

3. Fisheries

3.1. Benthos and shellfish

The sea floor is inhabited by a wide range of organisms. Some are buried in the sediments, others are attached to a substrate, some are slow and sluggish, and others are roving and rapid. More than 3050 species of benthic invertebrates inhabit the Barents Sea [3]. The benthic ecosystems in the Barents Sea have considerable value, both in direct economic terms and in their ecosystem functions. Scallop, shrimp and king crab are harvested in the region. Snow crab may be regarded as a potential commercial species in the Barents Sea. Many species of benthos, such as sea cucumber, snails and bivalves, are also of interest for bio-prospecting or as a potential food resource. Important fish species such as haddock, cod, catfish and most flatfishes primarily feed on benthos. Many benthic animals, primarily bivalves, filter particles from the ocean and effectively remove particulate matter from the water column. Others scavenge on dead organisms, returning valuable nutrients to the water column. Detritus feeders and other active diggers regularly move the bottom sediments around and therefore increase sediment oxygen content and overall productivity—much like earthworms on land.

The decline in the total biomass of benthos, from 1924–1935 to 1968–1970 [4], occurred throughout most of the Barents Sea and has been attributed to climate change by many investigators. The mechanism behind this biomass reduction is not clear, however.

The northern shrimp (*Pandalus borealis*) is distributed in most deep areas of the Barents Sea and Spitsbergen waters. The densest concentrations are found in depths between 200 and 350 meters. This species mainly feeds on detritus but will also scavenge for food. It is also important as a food item for many fish species and seals.

Red king crab (*Paralithodes camtschatica*) was introduced to the Barents Sea in the 1960s. Presently, it is an important commercial species. Adult red king crabs are opportunistic omnivores.

The snow crab (*Chionoecetes opilio*) is an invasive species deliberately introduced to this region. The first recordings of this species in the Barents Sea were in 1996. Since 2003, snow crab have been found in the stomachs of cod, haddock, wolffish and thorny skates, indicating that the crab abundance and settlement density have substantially increased.

The Iceland scallop (*Chlamys islandica*) is a slow-growing species common in all shallow areas (<150 m). It is usually associated with hard bottom substrate and most commonly in areas with strong currents [5]. The scallop is a filter feeder and is therefore highly dependent on seasonal phytoplankton production, which also has impacts on its growth [6]. The lifespan is 30 years and above.

There are eight species of squid inhabiting the Barents Sea [7]. The flying squid *Todarodes sagittatus* was a significant fishing resource in Norwegian waters during several periods up to1988 [8]. However, since then it has been almost absent from the waters and only sporadic catches have been recorded. *Gonatus fabricii* is another abundant squid species in the off shore waters of the Barents and the Norwegian Sea [9]. This species is important food for several bird and cetacean species, but could probably also be seen as a potential fishing resource.

3.2. Fish

More than 200 fish species are registered in trawl catches during surveys of the Barents Sea, of which nearly 100 occur regularly. The different water masses, together with bottom type and depth, are important factors determining the distribution of fish species. For pelagic species, the distribution and abundance of zooplankton are additionally important factors. The most important demersal fish species include Northeast Arctic cod (*Gadus morhua*), Northeast Arctic haddock (*Melanogrammus aeglefinus*), saithe (*Pollachius virens*), redfish (*Sebastes mentella* and *S. norvegicus*), Greenland halibut (*Reinhardtius hippoglossoides*), long rough dab (*Hippoglossoides platessoides*), wolffish (*Anarhichas lupus*, *A. minor* and *A. denticulatus*) and European plaice (*Pleuronectes platessa*), while the important pelagic species are Barents Sea capelin *(Mallotus villosus)*, polar cod (*Boreogadus saida)* and immature Norwegian spring-spawning herring *(Clupea harengus)*. In some warm years, increased numbers of young blue whiting (*Micromesistius poutassou*) have migrated into the Barents Sea. There have been large variations in abundance of most of these species. These variations are due to a combination of fishing pressure and environmental variability.

The recruitment of the Barents Sea fish species has shown a large year-to-year variability [2]. This variability in recruitment causes large variations in the biomass of pelagic forage fish, which are all either short-lived (capelin and polar cod) or spend only a short part of their lifespan in the Barents Sea (herring). The most important reasons for the recruitment variability are variations in the spawning biomass, hydrographic conditions, changes in circulation pattern, food availability and predator abundance and distribution. Recent work on larval drift has shown that even small changes in spawning locations can have a large impact on the drift pattern of fish larvae. Vikebø et al. [10] and Opdal et al. [11] investigated the drift of cod and herring eggs and larvae spawned at different locations along the Norwegian coast. Results showed that spawning further offshore and more to the south gave a much higher possibility for the larvae to end up west of Svalbard. By contrast, more northern spawning resulted in a higher proportion of larvae entering the Barents Sea. Also, retention of the larvae was affected by spawning site, and hence, the development stage for larvae when they reach the entrance to the Barents Sea. A report on the knowledge base in the Lofoten area showed that about 70% of the egg, larvae and juvenile stages of the total commercial stocks (measured in catch biomass) in the Norwegian and Barents Sea pass by the Lofoten-–Vesterålen area. About 12% of the total stocks (measured in catch biomass) spawn in the Barents Sea. The Lofoten–Vesterålen area is therefore a vulnerable key area for the recruitment to the commercial stocks in the Norwegian and Barents Sea [2].

Cod is the most important predator among fish species in the Barents Sea. It feeds on a wide range of prey, including larger zooplankton, most available fish species, including their own juveniles, as well as shrimp [2]. Cod prefer capelin as prey, and fluctuations of the capelin stock may have a strong effect on growth, maturation and fecundity of cod, as well as on cod cannibalism and hence recruitment to the stock. The role of euphausiids in the cod diet increases in the years when capelin stock is at a low level [12]. Also, according to Ponomarenko [13], inter-annual changes in euphausiid abundance are important for the survival of cod during the first year of life.

Capelin is an important consumer of zooplankton biomass produced near the ice edge. Farther south, capelin is the most important prey species in the Barents Sea as it transports biomass from northern to southern regions [14]. The Barents Sea capelin stock underwent drastic changes in stock size during the last three decades. Three stock collapses occurred in 1985–1989, 1993–1997 and 2003–2006, and data from 2015 suggest that the capelin may be headed towards a fourth collapse. The collapses had effects both downwards and upwards in the food web [15]. The release in predation pressure from the capelin stock led to increased amounts of zooplankton during the two first collapse periods. When capelin biomass was drastically reduced, its predators were affected in various ways. Cod experienced increased cannibalism, growth was reduced, and maturation delayed during the first capelin collapse. Sea birds experienced increased rates of mortality and total recruitment failures, and breeding colonies were abandoned for several years. Harp seals experienced food shortage and increased mortality because they invaded the coastal areas and were caught in fishing gears and because of recruitment failures. There is evidence for differences in how the three capelin collapses affected the predators. The effects were most serious during the 1985–1989 collapse, but much less during the second and third collapse. This was probably related to increased availability of alternative food sources during the two last periods of collapse.

Herring is also a major predator on zooplankton. The herring spawns along the Norwegian western coast, and the larvae drift into the Barents Sea as well as into fjords along the coast. The juveniles of the Norwegian spring-spawning herring stock are distributed in the southern parts of the Barents Sea. They stay in this area for about three years before they migrate west and southwards along the Norwegian coast and mix with the adult part of the stock. The presence of young herring in this area has been described to have a profound effect on the survival of capelin larvae and therefore on the recruitment to the capelin stock. The three collapses during the last three decades were all caused by recruitment failures, and all three were associated with rich herring year classes inhabiting the Barents Sea. However, while the presence of herring is seemingly a necessary factor for total recruitment failures of the capelin stock, it is not the only factor, since in some years the capelin recruitment has been relatively good in spite of moderate to high amounts of young herring in the Barents Sea.

Haddock is also a common species and migrates partly out of the Barents Sea. The stock has large natural variations in stock size. Water temperature at the first years of the life cycle may be used as an indicator of year class strength. Food composition of haddock consists mainly of benthic organisms.

Saithe is found mainly along the Norwegian coast, but also occurs in the Norwegian Sea and in the southern Barents Sea. The 0-group saithe drifts from the spawning grounds to inshore waters. The smaller individuals feed on crustaceans, while larger saithe depend more on fish as prey [16]. The main fish preys are young herring, Norway pout, haddock, blue whiting and capelin, while the dominating crustacean prey is krill.

Polar cod is a cold-water species found particularly in the eastern Barents Sea and in the north. It seems to be an important forage fish for several marine mammals, but to some extent also for cod. There is little fishing of this stock, and relatively little fisheries data. However, it is clear that the stock abundance is in decline.

Deep-sea redfish and golden redfish are important elements in the fish fauna in the Barents Sea, but due to heavy over-fishing, these stocks declined strongly during the 1980s and have since then stayed at a low level. Young redfish are plankton eaters, but larger individuals take larger prey, including fish.

Greenland halibut is a large fish predator with the continental slope between the Barents Sea and the Norwegian Sea as its most important area. It is also found in the deeper parts of the Barents Sea and the continental shelf. Investigations in the period 1980–1990 showed that cephalopods (squids, octopuses) dominated in the Greenland halibut stomachs, as well as fish (mainly capelin and herring). Ontogenetic shift in prey preference was clear with decreasing proportion of small prey (shrimp and small capelin) and increasing proportion of larger fish with increasing predator length. The largest Greenland halibut (length more than 65–70 cm) had a rather large portion of cod and haddock in the diet. The stock was over-fished leading to low (though uncertain) stock abundance in the 1980s, but a partial moratorium in the early 1990s led to stock recovery, and the stock is now assessed as above limit reference points.

The blue whiting has its main distribution area in the Norwegian Sea and Northeast Atlantic, and the marginal northern distribution is at the entrance to the Barents Sea. Usually, the blue whiting population in the Barents Sea is small. In some years, the blue whiting may enter the Barents Sea in large numbers and can be a dominant species in the western areas. This situation occurred from 2001 and during 2003–2007. Since then, the abundance has decreased strongly, but showed an increase in 2012. These fluctuations are probably due to a combination of variation in stock size and environmental conditions. In the diet of blue whiting, zooplankton (copepods, hyperiids and euphausiids) is dominant in the younger age groups, while fish is increasingly important as the blue whiting gets older [17].

3.3. Marine mammals

Marine mammals, as top predators and keystone species, are significant components of the Barents Sea ecosystem. Twenty-five species of marine mammals regularly occur in the Barents Sea, including: seven pinnipeds (seals and walruses); 12 large cetaceans (large whales); five small cetaceans (porpoises and dolphins); and the polar bear (*Ursus maritimus*). Some of these species are not full-time residents in the Barents Sea and use temperate areas for mating, calving and feeding (e.g., minke whale *Balaenoptera acutorostrata*). Others reside in the Barents Sea all year round (e.g., white-beaked dolphin *Lagenorhynchus albirostris* and harbor porpoise *Phocoena phocoena*). Some marine mammals are naturally rare, such as the beluga whale *Delphinapterus leucas*. Others are rare due to historic high exploitation, such as bowhead whale *Balaena mysticetus* and blue whale *Balaenoptera musculus*.

Marine mammals are important predators on the commercial fish species in the Barents Sea. However, their consumption estimations are associated with high level of uncertainty. According to Folkow et al., [18] and Nilssen et al., [19], marine mammals may consume up to equally much or even more fish than those caught in fisheries. Minke whales and harp seals have the largest consumptions and may together consume around 5 million tons annually of crustaceans, capelin, herring, polar cod and other gadoid fish (cod, haddock, saithe) [2]. Functional relationships between marine mammals and their prey seem closely related to fluctuations in marine ecosystems. Both minke whales and harp seals are thought to switch between krill, capelin and herring depending on the availability of the different prey species [20, 21, 19].

The only marine mammal species commercially harvested in the Barents Sea are harp seals and minke whale. Harp seal pup production estimates are based on data collected during the traditional Russian multispectral aerial survey. Since 2004, the abundance of harp seal pup production in the White Sea has been sharply reduced, according to these surveys. One of the key factors which caused the reduction in the harp seal pup abundance in the last years is the diminished ice extent due to warming. The changed ice conditions were responsible for the redistribution of animals in the pup period. Abnormal ice conditions in the White Sea possibly also led to higher natural mortality of pups.

4. Fisheries assessment

The benchmark assessment for North East Atlantic (NEA) cod was done in 2015 [22]. The assessment advised continuation of use of the Extended Survivors Analysis (XSA) model as a main tool for NEA cod assessment. Some changes in model configuration were recommended.

The main model used for assessment of key stocks is the Extended Survivors Analysis (XSA) [23, 24]. The model is generally fitted to the catch at age and natural mortality data and works similarly to most typical Virtual Population Analysis (VPA) back-calculating models. The back-calculations in these implementations work the same way, but they differ in the statistical methods used for “tuning” to indices of population size.

For North East Atlantic cod, saithe, the XSA was used as the main assessment method. For Norwegian Coastal cod, the “separable VPA” (SVPA) model proposed by [25] was used. This model assumes that fishing mortality can be separated into an annual component common to all ages of a same year and into a component at age common to many years. According to this

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model, fishing mortality in year i and age j or f (i,j) is defined as follows: f(i,j) = F(i) x S(j) where F(i) represents fishing mortality for year i and S(j) the exploitation pattern or selectivity at age j.

Haddock and beaked redfish (*Sebastes mentella*) are both assessed using statistical catch-at-age (SCAA) models. In contrast to the VPA methods, SCAA is a forward calculation method and is becoming more widely used throughout ICES fisheries with the introduction of the SAM (REF) model, which is used for haddock in the Barents Sea.

Where age data are uncertain or absent, an alternative model, the age- and length-structured Globally Applicable Area Disaggregated General Ecosystem Toolbox model or GADGET, is used for assessment. The model is currently used for the golden redfish, *Sebastes norvegicus*, and Greenland halibut.

5. Arctic Atlantic—Norwegian Sea, Iceland and Greenland Sea

5.1. Fisheries

5.1.1. Norwegian Sea

The Norwegian Sea is a deep open ocean system, covering around 1.1 million km^2 extending from the Norwegian coast and the continental slope west of the Barents Sea out into the open Atlantic, as far west as the Iceland Sea and Jan Mayen, and bounded to the south by the North Sea. The area covers two separate deep water basins, the Norwegian and Lofoten basins, with water depths of 3000–4000 m, while the shallower water is dominated by the Norwegian Atlantic current branch of the Gulf Stream [26]. As a result of this steady influx of warm water, the area, although mostly in the Arctic, is largely free of sea ice, and the zooplankton is dominated by *Calanus finmarchicus*, which in turn supports large pelagic stocks. In contrast with many of the other systems described here, there exists a sizable area outside national territorial waters, the so-called "banana hole," in the gap between the 200-nm zones extending east from Jan Mayen and west from the Norwegian coast. Fisheries in the Norwegian Sea are primarily targeted at three large wide-ranging pelagic stocks: Norwegian spring-spawning herring (*Clupea harengus*), mackerel (*Scomber scombrus*) and blue whiting (*Micromesistius poutassou)*, with a limited amount of horse mackerel (*Trachurus trachurus*) in the south. The region also has a high biomass of squid. There are several abundant pelagic stocks that span both the Norwegian and Barents Seas, notably the Norwegian spring-spawning herring which use the Barents Sea as a nursery area before moving to the Norwegian Sea at about age 3 or 4, and the beaked redfish which is caught in both the Norwegian and Barents Seas. The mackerel and blue whiting in the Norwegian Sea represent the northern extreme of stocks ranging down to the Iberian peninsula. There are thus significant connections between the Norwegian Sea and adjacent ecosystems, and consequently, much of the stock assessments are conducted on a wider scale than the Norwegian Sea alone. The seabed of the main basins is dominated by deep water benthos, while along the continental shelf closer to the Norwegian coast are a number of cold-water coral reefs. These corals are slow growing and support a high biodiversity and receive protection in the form of exclusion areas for bottom trawlers. The minke whale population described in the Barents Sea section passes through the Norwegian Sea on its migration route, and a fraction of the stock remains in the Norwegian Sea to feed in the summer, while the remainder continues to the Barents Sea, possibly based on the biomass of herring encountered en route [27]. Other main marine mammal predators in the region are larger whales, including humpbacks, blue whales and fin whales, as well as several species of dolphins, notably white-beaked (*Lagenorhynchus albirostris*) and white-sided (*Lagenorhynchus acutus*) dolphins, as well as harp and hooded seals. In addition to the top-down forcing imposed by the marine mammal predators, there is considerable bottom-up forcing arising from multiple large pelagic stocks feeding largely on the same plankton resource (Skjoldal et al. 2004). The recent large biomasses of mackerel and blue whiting are associated with a decline in the biomass of zooplankton.

The main fisheries target wide-ranging pelagic, and the assessment and management of these species are therefore conducted through an international ICES WG on widely dispersed species, WGWIDE [28], extending beyond the Norwegian Sea. In 2014, 13 countries reported catches of over 9000 tonnes of mackerel (with the Faroes, Greenland, Iceland, Ireland, Norway, Russia and the UK all reporting catches of over 75,000 tonnes) out of a catch of 1.4 million tonnes, 7 countries reported over 9000 tonnes of NSS herring (with the catch dominated by Norway and Russia) out of a total of 460,000 tonnes, and 11 countries reported over 9000 tonnes of blue whiting (dominated by the Faroes, Iceland, Norway and Russia) out of a catch of 1.15 million tonnes. Although discards are believed to exist, they are highly variable with either 0 or 100% discards when the entire haul is discarded. As a result, estimates of discards are difficult to compile and considered inadequate by the WG (although believed to be low for blue whiting).

Both mackerel and blue whiting are assessed with the SAM catch-at-age model [29]. Norwegian spring-spawning herring has been assessed with a VPA model, although at the time of writing, an ongoing benchmark process is reviewing the choice of assessment model.

The mackerel stock ranges from the Iberian coast to the northern Norwegian Sea and supports a highly valuable fishery. Although line fisheries exist in the south, the Norwegian Sea fishery is based on freezer trawlers, pelagic trawlers and purse seine vessels. The assessment is based on catch-at-age data, a recruitment index from the IBTS surveys in the North Sea, the Norwegian Sea ecosystem survey (IESSNS) and an SSB index derived from an egg survey, as well as tag recapture data. There is considerable uncertainty in the assessment of the stock, with the perception of the stock changing between assessments. In the absence of an agreed management plan, ICES gives advice on a MSY basis. Following the expansion of the mackerel stock into Icelandic and Faroese waters, no general agreement has existed between the main states catching the mackerel on distribution of the quota since 2009, and consequently, the sum of the declared quotas in 2015 was 1.24 million tonnes, which was 330 thousand tonnes above scientific advice.

The blue whiting stock also ranges widely in the East Atlantic, with the Norwegian Sea believed to be the key nursery area. The assessment showed a significant downward revision in 2015 in accordance with a reduction in the survey index. The assessment is considered to have high, but non-quantifiable uncertainties. The stock is managed with an ICES-approved precautionary HCR agreed between the EU, Norway, the Faroes and Iceland, and catch in 2014 was slightly below the advised quotas. The bulk of the catch comes from large pelagic trawlers (although demersal trawlers also target blue whiting in the Norwegian Sea), with 92% of the catch being taken in the first half of the year. The Norwegian Sea forms the main nursery area for the stock; however, most of the catches occur further south.

In contrast to the other main pelagic stocks, the NSS herring is largely confined to Norwegian Sea and adjacent Icelandic and Faroese waters, except for the nursery area in the Barents Sea (which is not subject to a commercial fishery). The management of the fishery is thus controlled by Norway and Russia, and a long-term management plan has been in place since 1999. The plan has been evaluated by ICES and found to be precautionary. Following a collapse to 0.1% of its previous SSB in the late 1960s, the Norwegian spring-spawning herring retreated to the Norwegian coast. However, an exceptionally large year class in 1983 led to the stock recovering and resuming a widely distributed habit, with spawning grounds near the Norwegian coast and feeding throughout the northern Norwegian Sea. A series of poor year classes led to a decline in the stock, to the extent that the 2015 assessment estimated the stock to be below the Bpa of 5 million tonnes, although predicted to stabilize above Blim. The fishery follows the annual migration of the stock. A fishery begins in January on the spawning aggregation near the Norwegian coast, no spring fishery, a summer fishery in Icelandic and Faroese waters and around Jan Mayen and Svalbard, and finally a fourth quarter fishery (taking the largest fraction of the catch) in the eastern Norwegian Sea. The Norwegian fleet is dominated by purse seiners (92%) and pelagic trawlers (8%), while the Russian fleet is a variety of trawl vessels. Within the Norwegian-administered Norwegian Sea, a minimum catch size of 25 cm restricts the fishery to largely targeting mature individuals.

In addition to the fisheries described above, a small developmental catch exists for *Calanus finmarchicus*. The Calanus is pressed to extract the oil, which is marketed as an omega-3 supplement, highlighting that as a species with low trophic level, the oil is unlikely to have accumulated pollutants. The remaining mass is sold as fishmeal. Although the fishery is profitable at the current small scale, and a harvest of 1% of the stock could produce in excess of 2 million tonnes of marine oils and protein [30], it is unclear whether the fishery could be commercially viable if it expanded beyond the relatively small market for omega-3 supplements.

5.1.2. Icelandic Waters

Although Iceland sits just below the Arctic Circle, the EEZ covers 758,000 km^2 and extends into the Arctic and adjoins Greenlandic waters to the west and the Norwegian Sea and Faroese waters to the north and east. Fisheries are of critical importance to the Icelandic economy. The country was one of the first to claim a 200-nm economic zone, and total landings in 2014 were 1017 tonnes—for a population of 323,000. Seafood exports represent 41% of total export value, and the fisheries and related industries comprise 25% of GDP in 2014. By far, the most economically important component of the fishery is on the cod stock, representing over a one-third of the value of the exported seafood, and the 2015–2016 quota of 239,000 tonnes equates to almost ¾ of a ton of cod per Icelander.

The extensive EEZ ensures that many stocks are largely or wholly within Icelandic waters. The major exception is a mixed pelagic fishery in the east, catching NSS herring, mackerel and blue whiting from the margins of the stocks in the Norwegian Sea (see above), as well as an Icelandic herring stock. The ocean redfish (principally *S. mentella* and *S. norvegicus*) extends into international waters and is regulated by NEAF. This is divided into several stocks as well as two species, although there is a dispute as to the number of biological stocks, and ICES advice is to avoid "disproportional exploitation rate of any one component." The other major fisheries are on cod, haddock and capelin, with Greenland halibut, ocean wolfish, plaice, shrimp and lobster also caught.

In addition to large vessels, the fishing sector is managed to encourage small boats (<15 m) to participate in the commercial fishery by allocating a fraction of the total quota to this sector, reflecting the importance of fishing as a source of employment. The main gears used for demersal fishing are bottom trawls, longlines, gillnets and Danish seines, while mid-water trawls and purse seines are the main pelagic gears.

A wide variety of stock assessment methods are used, depending on the stock biology and data availability, ranging from detailed analytic modeling to qualitative measures for some redfish stocks. For most stocks, a TAC is set based on either a MSY approach or an explicit HCR. For capelin, an escapement strategy is used. In addition to the stocks described in the Norwegian Sea section, the following assessment models are used for the major Icelandic stocks.

ADAPT-type models are used for the Icelandic herring stock and the haddock. Cod is assessed with a statistical catch-at-age model (implemented in AD model builder). Capelin uses a short-term forecast model to project from survey estimates to SSB, taking into account predation from cod, haddock and saithe, in order to set an escapement strategy TAC such that the final SSB in 95% likely to be above Blim. Greenland halibut uses a Baysean surplus production model. The GADGET age and length-structured model is used to provide assessment for golden redfish (*S. norvegicus*), tusk (*Brosme brosme*) and ling (*Molva molva*), where the ability to use length data directly is considered valuable. Other redfish (multiple *S. mentella* stocks) are assessed using qualitative or survey-based methods in the absence of more reliable data.

5.1.3. Greenland Sea

The Greenland Sea is bounded by Greenland, the Arctic Ocean, Svalbard, the Norwegian Sea, Iceland, and the Denmark Strait to the south (**Figure 3**). The cold and deep (>2000 m) Greenland Sea is separated from the deep and warmer southern Irminger Sea by a relatively shallow (maximum depth of 630 m), east-to-west-oriented submarine sill in the Denmark Strait. Along with the Norwegian Sea, it forms the Arctic Ocean's main outlet to the Atlantic. On the shelf area north of this sill, the hydrographical conditions are dominated by the cold southward-flowing East Greenland Current (EGC) which, to a large extend, is composed of Norwegian Deep Water with temperatures often below 0°C [31]. The EGC is formed in the Arctic by the

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cooling of warmer northerly flowing North Atlantic Water (NAW) that is taken into the Arctic by the Norwegian Atlantic Current. Warmer water enters the Greenland Sea Gyre where it undergoes cooling through contact with the Arctic Ocean and associated sea ice. Most part of the Greenland Sea falls under ICES area of North East Atlantic Fisheries Commission (NEAFC) XIVa and IIb2. The ICES provides scientific advice for fisheries in the area through its advisory committee which is used by the relevant management authorities, e.g., NEAFC.

Figure 3. Arctic Atlantic: The Greenland Sea, Iceland and Norwegian Sea.

Arctic zooplankton produced in Greenland Sea migrates with the sea currents into the Iceland and Norwegian Seas and contributes to the feeding for the large stocks of pelagic fish [40]. In the past decades, the Greenland Sea has experienced warmer temperatures due to increased influx of North Atlantic water [32] which may have a significant influence on the anticipated yields of commercial species in this area. Cheung [33] has projected 15–45% increases in maximum catch potential in Greenland Sea between 2005 and 2050. Greenland halibut (*Reinhardtius hippoglossoides*), red fish (*Sebastes* spp.), Arctic cod (*Boreogadus saida*), herring (*Clupea harengus*), blue whiting (*Micromesistius poutassou*), tusk (*Brosme brosme*) and capelin (*Mallotus villosus*) are important commercial fish species in Greenland Sea and adjacent areas. Capelin was historically the largest fish stock in the adjacent Iceland Sea area. However, since the mid-2000s, there is a decline in its recruitment and stock size probably due to an increase in the inflow of Atlantic water [34].

5.2. Fish and fisheries

The total number of fish species known from the Greenland exclusive economic zone (EEZ) is 269, whereas the lowest numbers of fish species with 47 are observed in the northeast of Greenland in the Greenland Sea [35].

Fisheries targeting marine resources off Greenland can be divided into inshore and offshore fleets. The majority of the Greenland fleet is comprised of approx 450 larger vessels and a big fleet of small boats. It is estimated that around 1700 small boats are dissipating in some sort of artisanal fishery mainly for private use or in the pound net fishery [36]. In East Greenland, fishing and other anthropogenic activities take place mainly in the southern parts.

The inshore fleet is constituted by a variety of different platforms from dog sledges used for ice fishing to small multipurpose boats engaged in whaling or deploying passive gears such as gillnets, pound nets, traps, dredges and longlines. The main targeted species are shrimp (*Pandalus borealis*), Atlantic cod (*Gadus morhua*), lumpfish (*Cyclopterus lumpus*), snow crabs (*Chionoecetes opilio*) and salmon (*Salmo salar*). The coastal fleets fishing for Atlantic cod, snow crab, scallops and shrimp are regulated by licenses, TAC and closed areas. Fishery for salmon and lumpfish is unregulated [36].

Apart from the Greenland fleet, the marine resources in Greenland waters are exploited by several nations, mainly EU, Iceland and Norway using bottom and pelagic trawls as well as longlines. The demersal offshore fishery is comprised of vessels primarily fishing Greenland halibut (*Reinhardtius hippoglossoides*), shrimp, redfish (*Sebastes mentella* and *S. norvegicus*) and Atlantic cod. Greenland halibut and redfish have been targeted since 1985 using demersal otter board trawls [36]. Longliners are operating on both the east and west coast with Greenland halibut and Atlantic cod as targeted species. Bycatches include roundnose grenadier (*Coryphaenoides rupestris*), roughhead grenadier (*Macrourus berglax*), tusk (*Brosme brosme*), Atlantic halibut (*Hippoglossus hippoglossus*) and Greenland shark (*Somniosus microcephalus*) (Gordon et al. 2003). The pelagic fishery in Greenland waters is conducted in East Greenland and currently targeted species are Atlantic mackerel (*Scomber scombrus*) and pelagic redfish (*Sebastes mentella*). A relatively small fishery for herring (*Clupea harengus*) is carried out in the border area between Greenland, Iceland and Jan Mayen. Additionally, Arctic cod (*Boreogadus, saida*), blue whiting (*Micromesistius poutassou*) and capelin (*Mallotus villosus*) are caught by the commercial fishery in the Greenland Sea and adjacent areas.

The main area of the Greenland Sea is part of divisions XIVa and IIb of the International Council for the Exploration of the Sea (ICES) and part of the convention area of the North East Atlantic Fisheries Commission (NEAFC). ICES provides scientific advice for fisheries in the area through its advisory committee which is used by the relevant management authorities, e.g., NEAFC. The demersal and pelagic offshore fishing together with longlines is managed by TAC, minimum landing sizes, gear specifications and irregularly closed areas.

Many species of cetaceans and pinnipeds feed in the Greenland Sea during the open water including walrus (*Odobenus rosmarus*), ringed seal (*Pusa hispida*), bearded seal (*Erignathus barbatus*), harp seal (*Phoca groenlandica*), hooded seal (*Cystophora cristata*) and bowhead whale (*Balaena mysticetus*). The Greenland Sea is an important whelping ground for harp seals and hooded seals. Hooded seal stocks in the area were quite large [37] and have been subject to commercial exploitation for centuries. However, giving an estimated total population of 84,020 hooded seals in 2013, this stock is below the conservation reference point in the precautionary harvest strategy developed by ICES and since 2007, the stock is protected from commercial hunt [38]. In contrast, harp seal are in abundance. The 2013 total abundance was estimated to be 627,410 with harvest level of only around 6000 per year [2].

Minke whales in the Norwegian Sea belong to the same stock as those feeding in the Barents Sea. The minke whales pass through on their way to summer feeding grounds in the Barents Sea, and a fraction remains in the Norwegian Sea.

There are few fisheries in the northern part of this area. In East Greenland, fishing and other anthropogenic activities take place in southern parts of east Greenland. Only small-scale subsistence hunting and fisheries take place near Ittoqqortoormiit. There are about seven marine fish species stocks which are harvested by commercial fisheries in Greenland Sea [39], mostly near Iceland. Arctic zooplankton produced in Greenland Sea migrates with the sea currents into the Iceland and Norwegian Seas and contributes to the feeding for the large stocks of pelagic fish [40]. The east Greenland drift ice forms a unique marine habitat under climate change that is not studied yet [41]. In the past decades, the Greenland Sea has experienced warmer temperatures due to increased influx of North Atlantic water [32]. Cheung [33] has projected 15–45% increases in maximum catch potential in the Greenland Sea from 2005 to 2050.

5.3. Fisheries assessment

5.3.1. Greenland halibut

The assessment model for Greenland halibut is a stochastic version of the logistic surplus production model using a new combined survey index and an Icelandic cpue index. Reference points as derived from this model are 30% BMSY as Blim, 1.7 × FMSY as Flim and an MSYB-trigger defined as 50% BMSY. BMSY and FMSY are inherited references in the model approach. An exploratory assessment on Greenland halibut using GADGET (Globally Applicable Area Disaggregated General Ecosystem Toolbox model) was presented in 2015.

5.3.2. Capelin

The assessment method is a stochastic projection of the stock starting from scientific acoustic measurements and finding the total allowable catch (TAC) that leads to the probability of the spawning stock biomass (SSB) < Blim being <5%. The initial quota is expected to be revised, based on in-season acoustic survey information in the autumn. The final TAC is expected to be set on the basis of survey information in the following winter.

5.3.3. Offshore Atlantic cod

No stock assessment can be undertaken for this stock, due to the lack of significant rebuilding since the stock collapsed in the late 1960s. Two scientific surveys targeting cod are considered reliable indicators of the stock status. However, they are associated with large uncertainty due to single large hauls.

5.3.4. Golden and Beaked redfish

GADGET is used for the assessment of golden redfish (*Sebastes norvegicus*) using commercial catch data and survey data from an Icelandic and a German survey. The demersal beaked redfish (*Sebastes mentella*) on east of Greenland and on the Icelandic slope is being assessed, based on trends in survey biomass indices from the Icelandic Autumn Survey in terms of the ICES "trends-based assessment" approach. Supplementary data used include relevant information from the fishery and length distributions from the commercial catch and the Autumn Survey.

5.3.5. Northeast Atlantic mackerel

The model for Northeast Atlantic mackerel is SAM, the state–space assessment model. In SAM, the "states" (fishing mortalities and abundances at age) are constrained by the survival equation and follow a random walk process. The variances of the random-walk processes on abundances and fishing mortalities are parameters estimated by the model. SAM is a fully statistical model in which all data sources (including catches) are treated as observations, assuming a lognormal observation model. The corresponding variances, the so-called observation variances, are also parameters estimated by the model. Observational variances can be used to describe how well each data source is fitted in the model and effectively corresponds to the internal weight given by the model to the difference data sources. The other parameters estimated are the catchabilities of the surveys. Uncertainties (standard errors) are estimated for all parameters and for all states (fishing mortalities and abundances at age).

6. GREENLAND–CONTINENTAL

6.1. Fisheries

The fisheries of the Greenland continent (**Figure 4**) are mainly subsistence and rights based on species such as Arctic char and various marine mammals such as harp seal, hooded seal and ringed seal as well as walrus, narwhal, beluga whale and bowhead whale. Rivers with Arctic char are throughout the Greenland coast, and fishing is typically by gillnets set close to shore. The Arctic char is known to spawn in winter in river outlets in South East Greenland and utilizes the coastal areas, but no comprehensive reviews have been published [42]. Little information is available regarding the total harvest and management of Arctic char in Greenland. They are an important fish in Greenland providing a food resource for Greenlanders. They are also important in terms of socio-economic value as they are of interest to tourism with anglers and fly fishing enthusiasts traveling to Greenland.

6.2. Fisheries assessment

As the Arctic char fisheries are prosecuted by local Greenlanders, there do not seem to be any published stock assessments. It is likely that assessments, if any, are carried out using catch-based methods.

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Figure 4. Iceland, Greenland, the Norwegian and Greenland Seas.

7. Baffin Bay-Davis Strait

Baffin Bay and Davis Strait are two large basins between Baffin Island and Greenland (**Figure 5**). According to Hamilton and Wu [43], Baffin Bay is a semi-enclosed ocean basin between Baffin Island and Greenland that connects the Arctic Ocean and the Northwest Atlantic, providing an important pathway for exchange of heat, salt and other properties between these

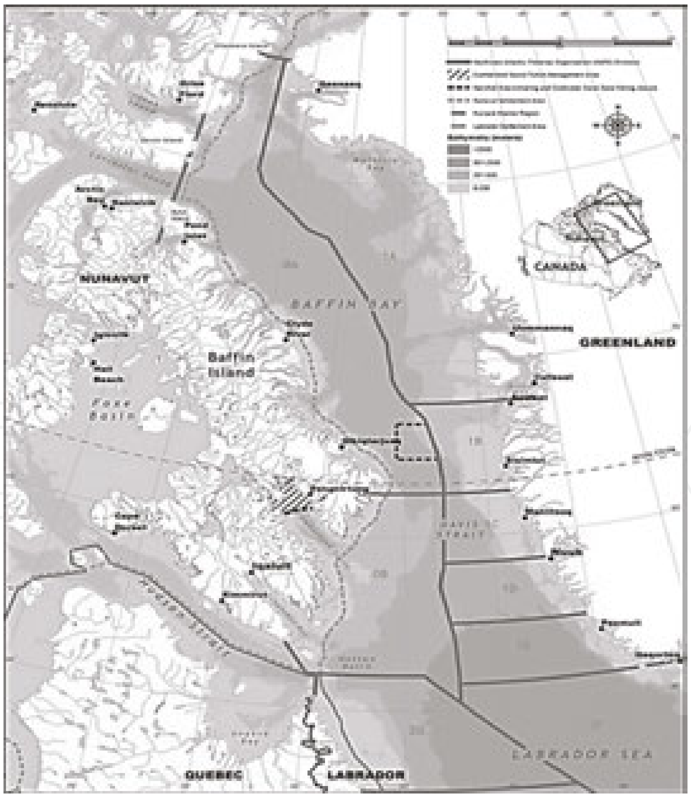

Figure 5. Map of Baffin Bay and Davis Strait.

2 oceans. To the south, the connection with the Atlantic is through Davis Strait, which is about 300 km wide and 1000 m deep. Baffin Bay's direct connection to the Arctic Ocean is far more restricted, being just 3 relatively small passages through the islands of the Canadian Arctic Archipelago (CAA). Arctic water also enters Baffin Bay–Davis Strait via the West Greenland Current which flows northwards along the western coast of Greenland. Melting ice sheets, changing sea ice conditions and changing weather also influence oceanographic conditions in Baffin Bay and Davis Strait. Trends and variability in the freshwater and heat input into the western North Atlantic via Baffin Bay–Davis Strait is of special interest because of the potential impact this input may have on global ocean circulation. Higher volumes of lighter, fresher water entering the Labrador Sea would increase stratification, with potential impact on the thermohaline circulation. The sinking of atmospherically cooled surface water in the Labrador Sea (the northwest arm of the North Atlantic) provides one of the driving forces for the "global ocean conveyor belt" which is vital in transporting heat and salt to northern latitudes. However, freshwater entering Baffin Bay is somewhat confined to the ocean's margins as part of a cyclonic circulation pattern, a principal component being the Baffin Island Current (BIC) that flows southwards along Canada's shelf and slope. Therefore, there is a potential for changes in this freshwater flux to impact the western North Atlantic ecosystem and fisheries by altering the physical properties of productive east coast banks and slope areas.

7.1. Fisheries

A total of 183 species of marine fish have been recorded in Baffin Bay–Davis Strait near shore and offshore areas and Lancaster Sound region [44]. Jørgensen et al. [45] found seven assemblages of fishes in Davis Strait and the southern Baffin Bay by a standard type of cluster analysis. They found four of the assemblages in Baffin Bay, two in Davis Strait and one mainly in Davis Strait but scattered into Baffin Bay. The most important fish in the region is the Greenland halibut (*Reinhardtius hippoglossoides*). The area has many other species as noted by Jørgensen et al. [46] who collected 45 fish species from northern Baffin Bay between 72° 02′ —76° 55′ N at depth 150–1418 m. Their surveys found two species Greenland halibut and the sea snail very common and represented in large numbers in almost all trawl hauls. Greenland halibut from Greenland, Newfoundland and Labrador spawn in the deep waters of Baffin Bay. Arctic cod (*Boreogadus saida*) is important species and a dominant trophic link between zooplankton and higher predators such as seals and sea birds. The capelin and herring are important forge fishes in Davis Strait. Greenland halibut and shrimp are the main commercially important fish species in the region.

7.1.1. Greenland halibut fisheries

Greenland halibut is the only large-scale commercial fishery in Canada's Arctic. This fishery was begun in 1996 as a small exploratory fishery but has been expanding [47]. It takes place throughout the year. Greenland halibut is caught in both inshore and offshore areas. In fjords, fish are caught by longlines either from small vessels or from the winter ice. The offshore fishery for Greenland halibut takes place in summer and autumn on the shelf slopes. On the Canadian side, NAFO Area 0 is divided into Area 0A (North, Baffin Bay) and Area 0B (South, Davis

Strait) (**Figure 6**). On the Greenland side, Area 1 is divided into 1A (offshore) and 1B (Baffin Bay), and 1C, 1D and 1 E (Davis Strait). Canada retains management authority for stocks in Subarea 0, while Greenland retains management authority in Subarea 1. NAFO Scientific Council conducts the stock assessment for the Subarea 0 and 1 for Canada and Greenland and recommends total allowable catch (TACs). Biomass, abundance, length frequency distribution and CPUE are the key metrics used in stock assessments and subsequent recommendations. The Greenland halibut fishery in western Baffin Bay is addressed by DFO's Integrated Fisheries Management Plan (IFMP) for NAFO Subarea 0 [47]. The Division 0A fishery quota is reserved exclusively for Nunavut, while the Division 0B quota is shared between Nunavut, Nunavik, Labrador, Newfoundland and Nova Scotia. Both mobile and fixed gears are used. In Area 0A, there is also a 100-t exploratory inshore quota. In 2015, the TAC is 16,000 tons in Div. 0A+ Div. 1AB, TAC for Div. 0B+ Div. 1CF is 14,000 tons, and the total TAC for the area (excluding inshore areas in Div. 1A) is 30,000 tons. In 2014, total catches were 31,083 tons [48]. In both areas of 0 Division, Greenland halibut catches are around 15,000 t in 2014, generating a landed value of more than $50 million/year. Inshore Cumberland Sound fishery is also an important winter fishery near Baffin Island. This fishery began in 1986 and has been operated during the winter months using longlines through holes in the ice. In 2005, a turbot management zone was established in Cumberland Sound with a TAC of 500 t. This quota is separate from NAFO Division 0B. In 1992, these catches peaked at 430 t. However, they were declined to levels below 100 t through the late 1990s. They peaked again to 245 t in 2003. However, harvest again declined significantly during the last decade because of poor ice conditions and reduced fishing effort (DFO 2008). Greenland halibut catches have averaged around 120 tonnes/year. Recently, there has been interest in a fishery in the open water season as well as exploring deeper areas (500–1000 m) in the center of Cumberland Sound, outside the winter fishing grounds and

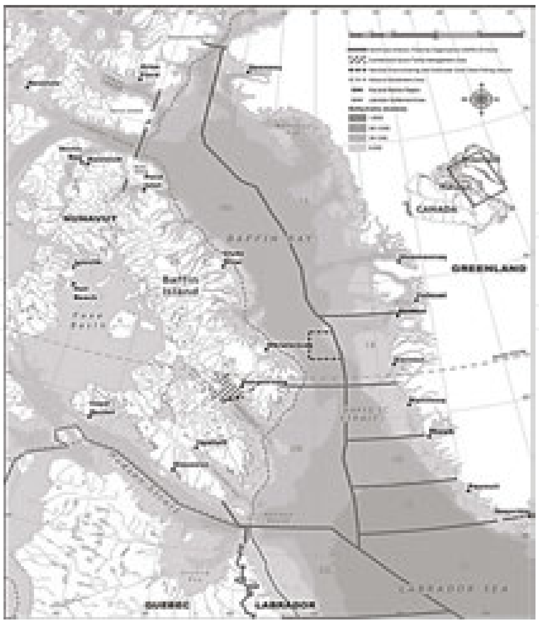

Figure 6. Northwest Atlantic Fisheries Organization Subareas and Divisions relevant to the Greenland Halibut fishery.

expanding turbot management areas up to the mouth of Cumberland sound. Greenland sharks are common bycatch. However, estimates of shark biomass, productivity and fishing mortality are unknown. Therefore, the ability to predict impact of Greenland halibut fisheries on the Greenland shark population is limited. In the eastern Baffin Bay, Greenland halibut can be found in all waters around Greenland both offshore and inshore, but the highest concentration is in NAFO division 1A inshore [49]. An inshore fishery for Greenland halibut developed in the beginning of the twentieth century, with the introduction of the longline in 1910. The majority of inshore fishing is concentrated near cities and settlements and in areas of iceberg producing glaciers having better fish catches. At present, this inshore fishery catches are around 20,000 tons [49]. The catches in Subarea 1 (offshore 1A + Div. 1B–1F) were 16,146 tons in 2014. Catches in these areas are taken by vessels from Greenland, Norway, EU-Germany Faeroe Islands and Russia mostly by trawl netting.

7.1.2. Northern shrimp fishery

In Baffin Bay, the Northern shrimp (*Pandalus borealis*) occurs on the continental shelf off West Greenland in NAFO Divisions 0A (Canada) and 1A–1F (Greenland) in depths between 150 and 600 m. For assessment and management purposes, the widely distributed northern shrimp population in East Canada, West Greenland and international waters in NAFO Sub-areas 0 and 1 is considered to be a single stock. Northern shrimp may represent a single meta-population within the Northwest Atlantic, but treating fishery management and ecological relationships at a smaller spatial scale appears consistent with precautionary fishery management [50]. Shrimp Fishing Area 1 (NAFO Division 0A) is a joint Canada–Greenland stock, and its management is bilateral, and annual assessments of this stock are done by NAFO Scientific Council. During 2005–2006, shrimp catches were recorded highest up to 157,000 tons. In 2012, a joint TAC of 105,000 tons was set by the Greenland Government for Subarea 1 (Greenland) and Div. 0 A (Canada) [51]. Canada has set a separate shrimp quota east of 60° 30′W. Canada has set a TAC of 16,921 for its fishery in SFA1 for 2012. Canadian shrimp catches have decreased in recent years, from about 7000 tons in 2003–2005 to 1300 tons in 2011. Northern shrimp fishery management is guided by the precautionary approach and ecosystem-based management approach [52]. The shrimp fishery in Greenland is regulated by individual quotas. In in western Greenland, the fishery for northern shrimp has declined during the last decade. However, as a response to climatic changes with higher temperatures in southwest Greenland, the stock is moving further north and it is possible that the area could regain its importance for commercial shrimp fisheries [51]. Bycatch of ground fish species by the small meshed shrimp trawls is a concern for these fisheries. Two species of wolffish, *Anarhichus denticulatus* and *Anarhichus minor* listed as threatened under SARA, are a bycatch in the northern shrimp fishery. To reduce it, an exclusion device known as the Nordmore grate was introduced into the Canadian shrimp fishery. This device sorts out the larger fish, allows them to escape while retaining the smaller shrimp, and has decreased groundfish mortality remarkably. There are gear restrictions in Greenland that include a cod-end mesh size of at least 40-mm stretched, sorting grids with 22-mm bar spacing to reduce finfish bycatch, the use of rolling rockhopper ground gear and toggle chains to keep trawl netting off the bottom [51].

7.1.3. Arctic char fisheries

Arctic char is a diverse and abundant resource in Nunavut. Its anadromous (searun) form is common in many river systems, primarily targeted by exploitation in small-scale fisheries. Several rivers flow into the Baffin Bay, Davis Strait and Cumberland Sound which support anadromous char. They spawn and over-winter in freshwater habitats, and adults normally spend the summers feeding in the marine waters of Cumberland Sound in the vicinity of their natal stream [53]. They feed in near-shore areas along the coast during the summer and migrate into fresh water during the fall. Arctic char is an important fishery in Nunavut coastal areas both for subsistence and commercial purposes. Subsistence fisheries are managed by hunters and trappers organizations, whereas Fisheries and Oceans Canada (DFO) is responsible for the management of the commercial harvest. Commercial harvest of char has been ongoing in several communities since the 1960s [54]. Combined commercial harvests in Nunavut between 2001 and 2008 have ranged between 74,124 and 95,558 kg [54]. Commercial harvest quotas are usually assigned to different rivers separately. To minimize the chances of over-exploitation, a system of exploratory licenses was set in place where a conservative quota is assigned to a river, which is then fished for five consecutive years gathering biological information on the harvested catch. These data are then used to assess the sustainability of the current harvest level. In the absence of abundance estimates, quotas are set at a conservation level using DFO precautionary approach model on the basis of best available information. Some mark recapture, weir enumeration and modeling estimates of abundance have been done in certain locations. However, their complicated migratory behavior violates many assumptions of these methods [54], and high uncertainty is associated with these results. The Cumberland Sound Arctic char commercial fisheries are operated on 17 stocks in the region [54]. All these fisheries take place in the fall during the upstream migration and utilize gillnets with 140-mm mesh size. Commercial quotas are set for each river, with none being greater than 5,000 kg [54]. Most watersheds sustaining Arctic char fisheries are fairly small, and these rivers probably support smaller populations However, no abundance estimates for these stocks have been done so far, and most of the fishery in the area is still at an exploratory phase. Although the distance between fish-bearing freshwater systems is comparatively larger, genetic data indicate that stock mixing does occur [55]. The community of Qikiqtarjuaq on western Baffin Bay traditionally harvests char from lake and river systems around Qikiqtarjuaq. Paddle Fiord, Nudluit and Confederation Fiord are important fishing areas. The quotas are usually for the areas, not for the water bodies. As compared to other Arctic char fisheries in Nunavut, very few studies have been conducted on Qikiqtarjuaq fisheries areas. Arctic char are fished from many waters close to Clyde River. There is no significant bycatch in Arctic char fisheries, and ecosystem impact of these fisheries is also negligible.

7.1.4. Other fisheries

The commercial fishery for snow crab (*Chionoecetes opilio*) was also once an important fishery in western Greenland, but its stocks are decreasing, and landings have dropped from 15,000 tons in 2002–2000 tons in 2007, and it is unlikely that a fishery for snow crab will develop in the near future in this area [56]. Snow crab are fished for using traps, but tangle nets may also be deployed. There are other small subsistence fisheries in near shore and fjords mostly in spring and summer.

Atlantic cod (*Gadus morhua*) were targeted using gillnets and trawls in West Greenland. The fishery was started in the 1920s and reached up to 400,000 tonnes per annum in the 1960s. However, due to over-fishing, the stock size declined and the fishery collapsed completely in the early 1990s. A recent survey in 2014 in West Greenland estimated at 110 million individuals with a biomass at 84,900 tons showing an increase. In 2014, the catches were 116 t. This fishery occurred in spring from March to May [36].

7.2. Fisheries assessment

A variety of methods are used to assess the major stocks in the Region. An Otter Trawl survey index (biomass) is the primary approach for assessment of Greenland halibut. Additionally, gillnet and longline surveys are conducted for the inshore stock of Greenland halibut in Cumberland Sound. For northern shrimp, the Northwest Atlantic Fisheries Organization uses a Bayesian model which incorporates cod predation on shrimp. For northern shrimp within Canadian waters, a survey biomass is used.

Arctic char fisheries have been assessed using trend analysis of age structure and mortality [57]. A number of modeling approaches for the assessment of Arctic char have been used including basic catch-based models such as depletion-corrected average catch, status quo models, Bayesian and life history invariant-based surplus production models [58, 59], age-structured models and zero-inflated generalized linear models (Xinhua Zhu, pers. comm.).

8. Hudson Bay

8.1. Fisheries

Cree and Inuit harvest fish during the open water season from James Bay and Hudson Bay estuarine or coastal waters (**Figure 7**). They do not have a tradition of offshore marine fishing. Fishing is a traditional social and cultural activity. Anadromous Arctic char are most sought after by Inuit in Nunavut and north of Kuujjuarapik in Nunavik. The reasons for its preference are predictable times and locations, growth and large size, and they are free of parasites. Further south, they harvest anadromous cisco, whitefish, longnose sucker and brook trout. Most fish are caught using gillnets set near the communities, either along the coasts or at river mouths. However, subsistence fisheries are not restricted in terms of the fishing area, season, or harvest. Capelins are also harvested when they spawn on the beaches. Subsistence harvests of cod and sculpin are much greater on the eastern side of Hudson Bay [60]. Commercially, marine fish species have not been found in sufficient quantity to support a marine fishery in Hudson Bay or James Bay. Small near-shore commercial fisheries for anadromous Arctic char have developed along the Kivalliq coasts and at Puvirnituq. There is an international standard meat-processing plant that processes fresh and frozen Arctic char for sale to domestic and international markets. This fish-processing operation has not received enough fish to consistently meet operating expenses. Transportation is a particular problem for these fisheries. Fishermen generally participate in the commercial fishery to subsidize subsistence harvests [60]. Commercial harvesting of coastal and estuarine fish especially Arctic char is also conducted by many communities along the Quebec coast during summer. Commercial harvest quotas at these locations are opened on request of the Hunters and Trappers Organizations. Commercial fisheries are closely regulated; however, over-harvesting can occur in areas with large subsistence fisheries. There is no marine trophy fishery in Hudson Bay or James Bay, and most sport angling is by local residents mostly for Arctic char.

Figure 7. Hudson Bay, James Bay and surrounding territories.

8.2. Fisheries assessment

Fisheries assessment has mainly been using trend analysis in age structure with the exception of a virtual population analysis approach used for the last formal assessment of the Diana River stock [61] on the Kivalliq coast, but recently data-limited models have been applied to historic data [57].

9. Canadian Archipelago and Arctic mainland

9.1. Canadian Arctic Archipelago

Arctic char are distributed across the Canadian Arctic Ocean including around the islands of the Arctic Archipelago (**Figure 8**). While this species may also be found in many rivers and lakes located in Canada's far north, the sea-run Arctic char are the most sought after for food and commercial uses. Arctic char are an important cultural, subsistence and economic resource in the Arctic. A number of commercial fisheries take place in the ocean tidal waters and river waters, as well as many subsistence fisheries for Canada's Inuit. Arctic char are a highly priced delicacy, marketed mainly fresh and frozen as whole-dressed fish and steaks. A small quantity is also processed into value-added products including smoked char and jerky.

Figure 8. The Canadian Arctic Archipelago, Mainland and Hudson Bay.

Arctic char have the most northerly distribution of any freshwater fish. This species has a body shape typical of most salmonids and exhibits great variability in form and coloration. In the Cambridge Bay area, for example, spawning fish have an orange back, sides and belly, and the intensity of color is most pronounced in males. Arctic char may be anadromous, moving downstream to the sea in spring and returning in the fall or may remain permanently in freshwater.

9.2. Fisheries

Arctic char fisheries are important for the Inuit and in the subsistence economy of many circumpolar people. These fisheries are concentrated near communities and are predominately conducted using gillnets. In 2004, it was estimated that the subsistence harvest in the Cambridge Bay area was about 50% the size of the commercial harvest. The very first commercial fishing effort of Arctic char began in Cambridge Bay.

Fisheries are prosecuted in tow fashions using weirs (mainly at Cambridge Bay) and gillnets. Weirs may be traditional stone weirs or made using conduit pipe to form a fence guiding the char into a trap. Gillnets are typically set close to shore in the marine and estuarine areas and within lakes during the winter.

A number of commercial fisheries take place in various river systems throughout the Canadian Arctic, with the majority occurring in Nunavut such as Cumberland Sound and Cambridge Bay areas. There are also exploratory fisheries to examine potential for future commercial char fishing areas.

Commercial landings were 57 tonnes in 2012, 52 tonnes in 2011, 29.4 tonnes in 2010 and 31.8 in 2009.Value:Landed value was $186,000 in 2012, $175,550 in 2011, $118,000 in 2010 and $133,367 in 2009.

Abundance status and trends data are limited given the geographic distribution and nature of the fisheries. However, there are indications that the commercial stocks are stable.

Conservation measures: Arctic char fisheries in the Canadian Arctic are managed in co-operation with respective co-management partners. Conservation measures for commercial fisheries include minimum gillnet mesh size and total harvest levels.

The Arctic char fisheries in the Nunavut settlement area are co-managed by the DFO, the Nunavut Wildlife Management Board, Regional Wildlife Organizations, and Hunter and Trapper Organizations, in accordance with the Nunavut Land Claims Agreement, the Fisheries Act and its Regulations, and in some communities by local Hunter and Trapper Organization bylaws. This ensures that the best available information guides Arctic char fishery management decisions. Integrated Fishery Management Plans are also in development for the main Arctic char commercial fisheries.

9.3. Fisheries assessment

DFO scientists, external experts and fish harvesters regularly review Arctic char stock assessments, and the results are published on the Canadian Science Advisory Secretariat Web site. Although these are data-poor stocks, the biological data collected from the fishery indicate a wide range of size and ages are present, with no loss of older age classes. This suggests that current levels of exploitation are likely sustainable.

Information about the condition and status of the oceans is also collected to better understand the effect of environmental conditions on char populations. For example, research activities have assessed: char biodiversity and trophic (feeding) variation in the Canadian North and its role in ecosystem structuring and function; the thermal ecology (temperature histories) of chars and how climate change might affect these; the link between climate change and the bioaccumulation of mercury; and changes in char populations as directly observed through community-based monitoring.

A number of approaches for the stock assessment of Arctic char have been used including basic catch-based models such as depletion-corrected average catch, status quo models), Bayesian and life history invariant-based surplus production models, age-structured models and zero-inflated generalized linear models [58, 59].

Commercial Arctic char fisheries in Nunavut are subject to a range of management measures designed to promote the sustainability and conservation of the char resource. Conservation measures include, but are not limited to minimum gillnet mesh size, total harvest levels and community-based monitoring. The management of these fisheries is complicated by the lack of harvesting data, the widespread distribution and biological complexity of Arctic char. New approaches using life history parameters as well as harvest and habitat information are being developed.

10. Canadian Arctic Mainland

10.1. Fisheries

Subsistence, commercial and sport fishing are important activities on Canadian Arctic Mainland, both culturally and economically. Most of commercial fisheries are confined to the lakes under some specific quota system, while subsistence fisheries are confined to rivers and stream in the vicinity of the communities. There are two distinct fishing seasons, summer and winter. In Mackenzie River Basin, fish production rate is low because of late maturity and slow growth rate [62]; however, standing stocks of large size fish are high. The remote locations of commercial fisheries in Mackenzie River Basin are a limiting factor, and most of the commercial fisheries are not viable. Because of low species diversity and low productivity, Mackenzie River Basin is less resilient to anthropogenic impacts. Commercial fisheries in Mackenzie River Basin are dominated by whitefish, and other low-value fish, e.g., burbot, suckers, are usually discarded. Lake whitefish has the ability to respond to the exploitation and is the basis of its success (Healey 1980). Reliable data on the actual fish yield from Mackenzie River Basin is lacking. Fish stocks in the Mackenzie Great Bear sub-basin have been assessed but not on a regular basis. Harvesting of different fish species by recreational and commercial fishers is regularly monitored by DFO. Great Bear Lake is world renowned for its trophy lake trout. There was a decrease in the harvest of lake trout during the 1970s up to 1980s. However, conservation measures have been adopted including catch release practice and the use of barbless hooks. The current harvest of lake trout in Great Bear Lake is below the maximum sustainable yield [63, 64].

Subsistence fisheries occur in the Inuvialuit, Gwich'in, Sahtu and Deh Cho areas of lower Mackenzie River Basin [65]. Broad whitefish and lake whitefish are important species in subsistence catches along with inconnu and lake cisco. The subsistence fishing has declined in recent years, due to less dependency on dogs. Because of its high productivity, the lower Mackenzie River broad whitefish is able to withstand commercial and subsistence exploitation. Broad whitefish is one of the most important species to the aboriginal subsistence fisheries in the lower Mackenzie River and Delta [66, 67]. The Fisheries Joint Management Committee

(FJMC) works jointly with DFO to co-manage all fish, fish habitat and marine mammals within the Inuvialuit Settlement Region and directly advise the Fisheries and Oceans on fisheries issues. The committee is responsible for collecting harvest information and making recommendations on subsistence quotas for fish and harvestable quotas for marine mammals. People from the communities of Tuktoyaktuk, Aklavik, Inuvik, Ft. McPherson, Tsiigehtchic and Ft. Good Hope harvest broad whitefish for subsistence and commercial purposes. The Tetlit Gwich'in First Nation of Fort McPherson catches broad whitefish from the Peel River for domestic use [68]. Annual catches are around 10–12 thousand fish per year. Changing lifestyles and a less use of dogs for transportation have decreased the overall fish harvest [68]. The Rat River is associated with a key subsistence fishery for the Gwich'in of the Northwest Territories, the Rat River Dolly Varden char (*Salvelinus malma*). Rat River Dolly Varden char are a largely anadromous population, migrating from the Arctic Ocean up through the Mackenzie Delta to over-winter in the spring-fed pools of water known as Fish Hole on the headwater tributary Łuk Njik, Fish Creek [69]. Fisheries in Great Slave Lake Basin include subsistence, sport and commercial fishing. However, reliable up-to-date data are available for the water areas under commercial fisheries, for example Great Slave Lake. There are six fish management areas in Great Slave Lake with each area having its own management plan. Its east arm and certain inshore areas are closed to commercial fishing; however, east Arm is managed for a trophy lake trout fishery. Commercial fish catch in Great Slave Lake is the biggest fishery in the Mackenzie River Basin and catch about 1100 t of which 80% is lake whitefish and 10% is pike [70]. Exploitation of fish stocks in Great Slave Lake has affected fish populations in some cases, e.g., the lake trout population declined in west basin 40 years ago [71, 72]. There is a reduction in commercial fisheries since 1990 because of reduction in effort results from lifestyle changes. Information on fish stocks and harvest is not complete, and management usually adopt a precautionary approach towards management. There are also reports of reduction in inconnu populations in some of the major tributaries to Great Slave Lake (VanGerwen-Toyne et al. 2013). However, whitefish stocks and the commercial harvest of this species seem to be sustainable [72]. At present, commercial harvest is around 500 tonnes against a quota of 1800 tonnes. Eigty percentage of the catch is composed of lake whitefish with about 10% cull. Great Slave Lake Advisory Committee (GSLAC) advises DFO on fishery management issues and ensures long-term conservation of fish and fish habitat. All communities living in Great Slave Lake Basin have subsistence fisheries which are poorly monitored. Traditional knowledge surveys and recent evidence suggest that the subsistence harvest was less than 5% of the total for the commercial harvest [73].

Whitefish make up 68% of the overall subsistence catch. Kakisa and Tathlina lakes support important walleye fisheries which account for over 70% of the walleye harvested commercially each year in the N.W.T. [74]. All three important fisheries including commercial, subsistence and sport fishers are using the fish stocks in the Liard sub-basin. Watson, Frances and Simpson lakes are popular for lake trout and northern pike. Lake trout stocks are deteriorated in Watson Lake. White sucker, northern pike, burbot, walleye, lake whitefish, inconnu and Arctic grayling are important part of the subsistence fishery in the Liard sub-basin [75]. The main fishery management issues standing out in the Mackenzie River Basin include the potential for over-harvesting of migratory stocks which may also be fished in other areas, the potential for damage to harvested fish stocks from winterkill or summer warming, and the potential for adverse impacts from the development of pipeline, transportation, mining and hydroelectric developments.

10.2. Fisheries assessment

A variety of assessment models and methods have been used for stock assessment. Survey and commercial catch rate indices have been used in Great Slave Lake and other fisheries. Trends in age structure and catch curve analysis is the most frequent approach, but surplus production models have been applied.

11. Alaska

11.1. Fisheries

Arctic Alaska consists of the Chukchi and Beaufort Sea coasts (**Figure 9**). On the Chukchi Coast, the Noatak River produces a large run of chum salmon that maintain a Kotzebue-based commercial fishery. Many thousands of anadromous Dolly Varden over-winter the lower 300 km of the river and spawn in some of the river's tributary streams. This system is known for the large size of its Dolly Varden, and the current state record 8.9 kg (19.75 lbs.) was taken in 1991 from the Noatak River. Whitefish, Arctic grayling, burbot and northern pike are resident in the Noatak River. Inconnu use the lower reaches of the river for feeding during the spring of the year, but are not known to spawn there. Both the Selawik and Kobuk rivers support spawning populations of Inconnu in their upper reaches. (http://www.adfg.alaska.gov/index.cfm?adfg=ByAreaInteriorNorthwest.moreoverview).

Figure 9. Continental Alaska and coastal seas.

Rivers on the Beaufort Sea coast have stocks of Arctic char that are harvested for subsistence and sport. The largest river is the Colville River where subsistence harvesting is done using gillnets. Arctic cisco (*Coregonus autumnalis*) and least cisco (*C. sardinella*) are harvested in the Colville River Delta near Nuiqsut, Alaska, after ice forms in the fall [76]. Arctic cisco targeted by the fall fishery derive from spawning stocks in the Mackenzie River of Canada. Young-of-the-year fish are recruited into the Colville region during August or September, aided by westerly coastal currents generated by predominantly easterly winds. In contrast, anadromous least cisco, harvested as the primary bycatch in the fishery, spawn and winter entirely in the Colville delta and lower river. Moulton et al. [76] reported on fishery monitoring for the 20-year period 1985–2004. During this period, effort in the subsistence fishery showed an increasing trend. Arctic cisco, the target species, averaged over 65% of the annual observed catch, and least cisco averaged 22%. From 1985 to 2002, total harvest of arctic cisco for the combined subsistence and commercial fisheries averaged 38,600 fish (15,958 kg) per year, ranging from a low of 5859 fish (2799 kg) in 2001 to 78,254 fish (31,340 kg) in 1993. During the same period, catches of least cisco averaged 18,600 fish (5819 kg), ranging from a low of 6606 fish (2014 kg) in 2001 to 33,410 fish (11,319 kg) in 1985. The subsistence fishery caught 56% of the total arctic cisco harvest and 42% of the least cisco harvest (in numbers of fish). In the six years for which estimates of both harvest and population level were available, total estimated annual harvest of arctic cisco within the Colville River Delta averaged 8.9% of the available fish, with yearly estimates ranging from 5.4 to 12.9%. For least cisco, the average annual removal rate was 6.8% (range 2.9–13.8%).

11.2. Fisheries assessment

Assessments have used age-structured and hydro-acoustic models and environmental models in the case of Arctic cisco [77].

12. Beaufort Sea

12.1. Fisheries

The Beaufort Sea is shared by Alaska and Canada (**Figure 10**). On both sides, there is no commercial fishing on marine fish. Historically, there was a commercial fishery on the USA side for Arctic Cisco. The fisheries now are for subsistence with moderate harvests by Inuvialuit and Alaskan aboriginal peoples of marine mammals, Dolly Varden char, *Salvelinus malma*, and Arctic Cisco, *Coregonus autumnalis*.

History of commercial fisheries in Beaufort Sea is dated back prior to 1960s; however, an economically viable commercial fishery has not been implemented in the region. Most fisheries in the region have focused on harvesting large anadromous broad whitefish, *C. nasus*. These are caught by gillnets along the coast in summer or when they enter freshwater rivers to spend the winter. Broad whitefish grow to a large size and have higher-quality meat. However, because of limited local markets and high cost of transportation, a commercial fishery was not developed.

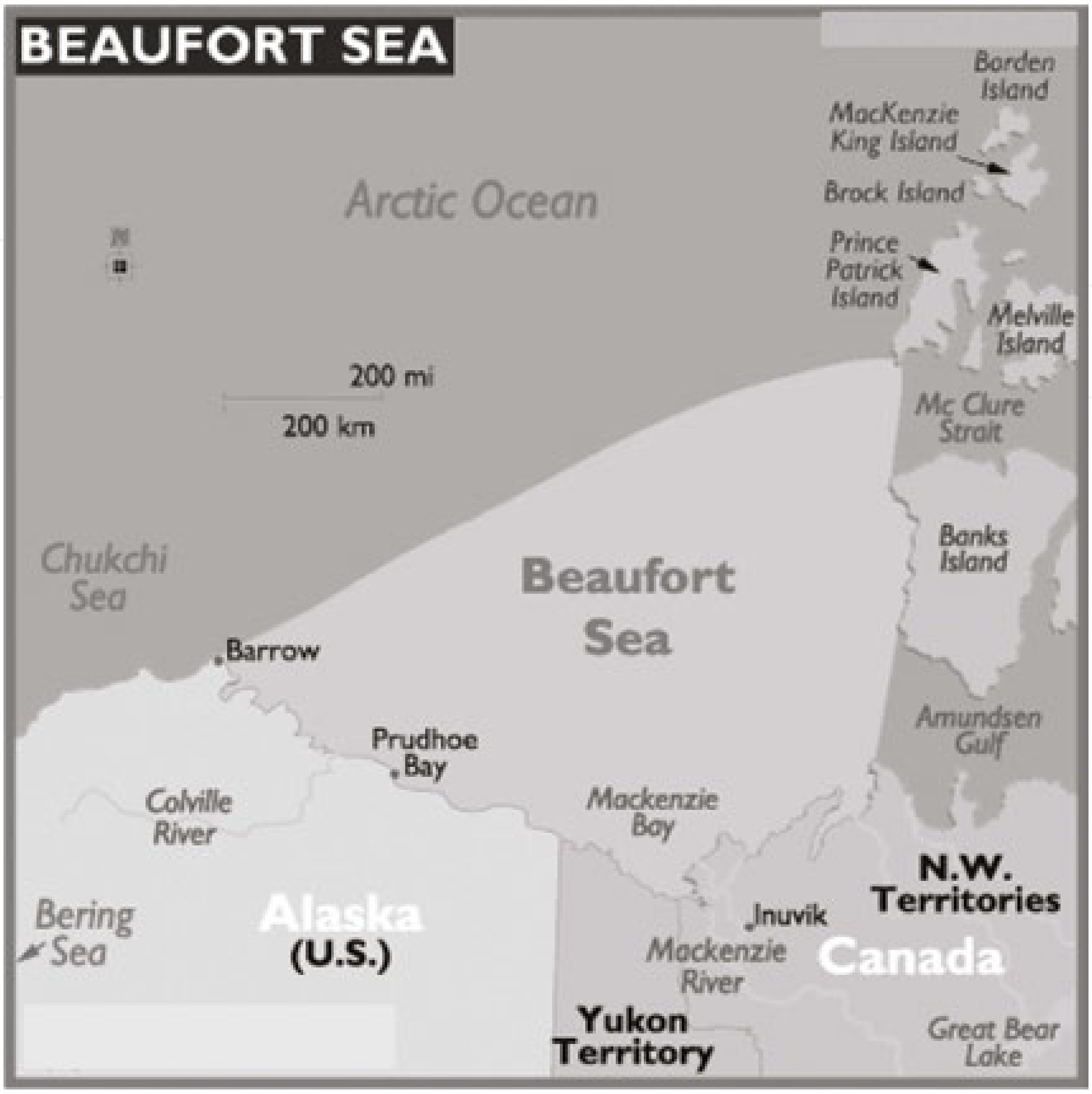

Figure 10. The Beaufort Sea.

Dolly Varden (*Salvelinus malma*) char west of the Mackenzie River were once thought to represent a distinct form of Arctic char (*Salvelinus alpinus*). They inhabit the Rat River and its tributaries. They are harvested mostly for subsistence purpose. However, in two areas Big Fish River and Rat Rivers, they were harvested both by subsistence and commercial fisheries. Arctic char typically occur in river systems to the east of the Mackenzie River drainage (e.g., Hornaday River, Kuujjua River).A Fisheries Joint Management Committee (FJMC) works jointly with DFO to co-manage all fish, fish habitat and marine mammals. The FJMC has the power to directly advise the Minister of Fisheries and Oceans on fisheries issues. The committee is responsible for collecting harvest information and making recommendations on subsistence quotas for fish and marine mammals. The FJMC also monitor sports fishing in the area. Community consultations are essential part of fisheries management in the area. The FJMC has a research budget and provides funding to complement traditional knowledge and science to solve resource management issues. Canadian federal government and the Inuvialuit people of the western Arctic have signed an agreement in 2011 to maintain fishing limits in the Beaufort Sea as a step towards a comprehensive ocean management plan for the Beaufort Sea. At present, commercial fishing does not exist in the Beaufort Sea, but there were many experimental applications in fishing license since 2000. The melting of sea ice has opened many waterways of the Arctic that led to boats, commercial vessels and fishing boats coming into the region. Integrated management framework for fisheries in the Beaufort Sea requires future commercial fisheries to have the support of the Inuvialuit living in the area.

Mathias [78] notes that main subsistence food for the Canadian Inuvialuit comes from beluga whale, broad whitefish, Arctic char, ringed seal, inconnu, humpback whitefish, and Arctic cisco. Fisheries productivity, or even biomass, on the Canadian Beaufort shelves, is unknown. There have been no systematic surveys of demersal and pelagic fish (other than larval fish) in the Canadian Beaufort Sea, although some locations have been fished with gillnets, beach seines, fyke nets and small mid-water trawls. In fact, Byers [[79], p. 40] stated: "The distribution and ecology of deep-water, off-shelf fish communities of the Canadian Beaufort Sea remain mostly unstudied. This is likely due, in part, to inaccessibility due to ice-cover and (until recently) a historical lack of industrial interest in abyssal regions." Mathias [78] noted that evidence suggests the Canadian shelves may be less productive than the Alaskan Shelf because they are less influenced by inflow from the productive Bering Sea and there may be other productivity differences brought about by the massive depositional environment caused by the Mackenzie River.

The Alaskan Shelf survey of the Beaufort Sea took place from the edge of Barrow Trough to ~109 km east and fished from 40 to 500 m, crossing the shelf break. A standardized bottom trawl survey quantified the distribution and density of demersal fish. Biomass estimates were produced for two depth strata (40–100 m and 100–500 m), and the two estimates were summed to provide a total biomass estimate of 18 kg/ha for a 6280-ha area of the shelf. Arctic cod made up 81% of the catch, while Bering flounder and walleye pollock together made up another 4%. The depths sampled were considered appropriate for a potential commercial fishery on the continental shelf and upper continental slope, but unlikely to occur in very shallow, near-shore areas.

On the same 6280-ha sampling site of the Alaskan Shelf, pelagic mid-water trawls and hydro-acoustic gear measured biomass estimates for Arctic cod of 19.2 kg ha–1 in the 40- to 100-m-depth range, and 53.7 kg ha^{-1} in the 100- to 500-m-depth range [80]. These densities may be compared with the estimate of unfished biomass for demersal Arctic cod from otter trawls, 18 kg ha^{-1} (=1.8 mt km^{-2}). The results of this fisheries survey on the Alaskan Shelf suggest that regardless of what species a commercial fishery targets, Arctic cod may constitute a significant bycatch [81]. Demersal fish were only 6% of the catch by mass; the overwhelming biomass was brittle stars. Arctic cod dominated fish catches, comprising 81% of fish biomass. Eelpouts made up 11% of the fish catch, while Greenland halibut were 0.7%, and walleye pollock and Pacific cod together (neither of which is reported from the Canadian Beaufort Sea) made up 2%.

12.2. Fisheries assessment

Assessments of key marine mammal species, such as Bowhead Whale are done by aerial survey and a Potential Biological Removal (PBR) model. Assessment of Dolly Varden has been done using surplus production and age-structured models (X. Zhu, DFO personal communication).

13. Chukchi Sea

13.1. Fisheries

For most fish stocks within the Chukchi Sea, stock size was insufficient to support commercial activity (**Figure 11**). Three stocks: snow crab (*Chionoecetes opilio*); Arctic cod (*Boreogadus saida);* and saffron cod (*Eleginus gracilis*) are of sufficient size to support commercial activity [82, 83].

Figure 11. The Chukchi Sea.

http://dx.doi.org/10.5772/62347

13.2. Fisheries assessment

Little formal stock assessment has been done, but density-based estimates have been used for assessment. Stock size has been inferred from catch effort data from surveys.

14. Siberia

14.1. Fisheries

The nature of Siberian fisheries is relatively unknown because assessments, if any, are published in Russian and not disseminated broadly (**Figure 12**). It is likely that the fisheries are similar to the Canadian coastal and inland fisheries which are prosecuted using gillnets and are usually interception fisheries capturing various species during their migrations for spawning or over-wintering. Siberia does contain a number of large rivers and Chum Salmon, *Orcorhynchus keta*, exists as far along the coast as the Lena River. The fisheries are likely on Pacific salmon, broad whitefish, inconnu, Arctic Cisco and Arctic char.

Figure 12. Continental Russia featuring Siberia.

14.2. Fisheries assessment

As noted above, published assessments in English are not known, and therefore, stock assessment models are unknown.

15. General aspects of assessment

The Arctic region shows wide variation in the nature of fisheries and the practice of stock assessment. The differences are as great within the marine areas compared to the freshwater fisheries. For example, the Barents Sea has large-scale industrial fisheries with total harvest near to 2 million tonnes, mainly from bottom trawl harvest, whereas an area comparable in size and latitude, the Beaufort Sea, has a tiny fraction of that harvest from subsistence activities with no commercial fisheries. The key species are much different with the Barents Sea being dominated by groundfish, especially Gadiods, while the fisheries in the Beaufort Sea are mainly on marine mammals and anadromous fish such as Dolly Varden char. Stock assessment of the Barents Sea fisheries is highly sophisticated, deploying a variety of analytical population models such as extended survivor analysis. In contrast, with the exception of recent assessments of Dolly Varden char, the Beaufort Sea stocks are not modeled and only indicator values are used in assessment.

There is likely less variation in the nature and assessment of freshwater fisheries. A large proportion of freshwater fisheries are prosecuted as interception fisheries using gillnets. Assessment is mainly regarding demographic trends in size at age although recently, surplus production and age-structured models have been applied in analysis. Data-limited assessment tools hold much promise for freshwater assessments, and the incorporation of fisher and aboriginal traditional knowledge through methods such as the traffic light approach is likely to be important in the future.

16. Conclusion

16.1. Future trends in arctic fisheries

16.1.1. Potential and realized effects of climate change

Climate change will have the most profound effect on the aquatic ecosystems of the Arctic [82, 83]. It has already been noted that the range of demersal species in the Barents Sea has shifted northward in recent years as there is less and less multiyear sea ice. Shift in Barents Sea stocks northwards. Ice-based ecologies of animals such as seals and Arctic cod in the Canadian Archipelago will shift even further northwards, and lower overall population sizes will occur. Access to fishing areas in the central offshore will be increased with unknown results in terms of harvest and management. Some species will increase growth and colonization, and increases in abundance of species more typical of temperate areas will occur.

16.1.2. Use of data-limited and traffic light approaches

Traditional assessment methodologies with a full range of fishery-dependent and fishery-independent metrics may not be possible for many of the small widely spread artisanal fisheries of the Arctic. However, there has been much new research in the area of data-limited fisheries assessment [58, 83]. These methodologies may be well suited to areas where sampling for detailed time series of demographic traits and other metrics is difficult. As well, for community-based fisheries where traditional ecological knowledge may exceed the knowledge based on scientific data collection approaches such as the traffic light approach that uses the sum of series of relatively "soft" indicators may be more effective for stock assessment than traditional methods from industrial fisheries.

16.1.3. Development and application of advanced population models

For areas with large-scale industrial fisheries such as the Barents Sea, ongoing development of advanced population models will surely happen in the future. The population models will likely include both fishery and stock statistics but environmental factors as well. Bayesian approaches to stock assessment are likely to grow in importance to be able to take advantage of prior knowledge and provide multiple options to managers.

16.1.4. Development and application of ecosystem models

Ecosystem models such as ECOPATH-ECOSYM may gradually mature so that they can be used for the development of annual quotas—taking into account the environmental conditions as well as stock and fishery. The incorporation of ecosystem-based models will be important to predict the effects of climate variation on yield and should be part of the fisheries manager's toolkit.

Ecosystems, fisheries and stock assessment are highly variable around the Arctic region. Understanding of Arctic fisheries is as complex as any other part of the world, if not more so. There will be great advances tailored to the Arctic fisheries assessment as understanding becomes clearer with more integration of scientific and traditional ecological knowledge.

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