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Review of the research knowledge and gaps on fish populations, fisheries and linked ecosystems in the Central Arctic Ocean (CAO)

Pauline Snoeijs-Leijonmalm (SU), Hauke Flores (AWI), Filip Volckaert (KU Leuven), Barbara Niehoff (AWI), Fokje L. Schaafsma (AWI), Joakim Hjelm (SLU), Jonas Hentati-Sundberg (SLU), Susa Niiranen (SU), Anne-Sophie Crépin (KVA), Henrik Österblom (SU)
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Contact: Rocio Suarez Jimenez

E-mail: *EASME-EMFF-CONTRACTS@ec.europa.eu*

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Snoeijs-Leijonmalm P[1], Flores H[2], Volckaert F[3], Niehoff B[2], Schaafsma FL[4], Hjelm J[5], Hentati-Sundberg J[5], Niiranen S[1], Crépin A-S[7], Österblom H[1]

[1] Stockholm University (SU), Sweden
[2] Alfred-Wegener-Institute Helmholtz-Zentrum für Polar- und Meeresforschung (AWI), Germany
[3] Katholieke Universiteit Leuven (KU Leuven), Belgium
[4] Wageningen Marine Research (WMR), The Netherlands
[5] Swedish University of Agricultural Sciences (SLU), Sweden
[6] Royal Swedish Academy of Sciences (KVA), Sweden

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List of abbreviations

CAFF	Conservation of Arctic Flora and Fauna (a working group of the Arctic Council)
CAO	Central Arctic Ocean (the LME as defined by PAME)
CFP	Common Fisheries Policy (EU)
DM	Dry Mass
EEZ	Exclusive Economic Zone
EFICA	European Fisheries Inventory in the Central Arctic Ocean
FiSCAO	Expert Group for Fishes in the Central Arctic Ocean
ICES	International Council for the Exploration of the Sea
LME	Large Marine Ecosystem (developed by the US National Oceanic and Atmospheric Administration (NOAA) to identify areas of the oceans for conservation purposes)
MSY	Maximum Sustainable Yield
PAME	Protection of the Arctic Marine Environment (a working group of the Arctic Council)
RCP	Representative Concentration Pathway trajectory adopted by the IPCC in its Fifth Assessment Report (2015)
SES	Social-Ecological System

Executive Summary

This report presents a review of the research knowledge and gaps on fish populations, fisheries and linked ecosystems in the Central Arctic Ocean (CAO). The CAO comprises the deep basins of the Arctic Ocean beyond the shelf break, which largely overlap with the High Seas of the Arctic Ocean, i.e. the marine areas outside the Exclusive Economic Zones (EEZs) of the Arctic coastal nations. The authors of the report are members of the European Fisheries Inventory in the Central Arctic Ocean (EFICA) Consortium. This study was funded by the European Commission as an EU contribution to the international cooperation within the *Agreement to Prevent Unregulated High Seas Fisheries in the Central Arctic Ocean*.

The report contains desk-based research, using scientific research data bases as well as any available research performed by the EFICA Consortium partners and EU institutions or others. In Chapters 2-8 the authors review the literature and identify specific knowledge gaps. The gap analyses involve comparisons of actual knowledge with desired knowledge on the fish stocks of the CAO to be able to evaluate possibilities for future sustainable fisheries in the area. Chapter 1 is an introductory chapter, and Chapter 9 presents a holistic gap analysis based on Chapters 2-8 and recommendations for research priorities and the next steps.

The critical gap analysis highlights that the knowledge gaps for the CAO are enormous and obstruct any quantitative analyses of its fish stocks. This agrees with the conclusions from the Fifth FiSCAO Report (FiSCAO 2018). While data for the physical environment in the CAO (oceanography, bottom topography and ice-cover dynamics) would be sufficient for fish stock modelling and assessment, there is a massive lack of biological and ecological data. The CAO is not a closed system and some aspects of the shelf seas are of high relevance for the CAO, notably connectivity of fish stocks and fish species moving north with climate warming. Scientific research and monitoring programs are established in the shelf seas, and new data are constantly being produced.

Fish stock data are available from scientific projects and monitoring programs for some of the shelf seas (Barents Sea, Bering Sea, and to a lesser extent for the Beaufort Sea and the Chukchi Sea). Data exist also for the Russian shelf seas (Kara Sea, Laptev Sea, East Siberian Sea), but these data are not internationally available, while for the areas north of Canada/Greenland data are missing; they do not exist because of the severe ice conditions there. More data from all shelf seas may be hidden in reports that are not publicly accessible. We recommend to make current knowledge generally available by translating key publications and identification of valuable data reports.

Research priorities comprise the collection and analysis of primary data in the CAO, and – to a limited extent – from adjacent waters through collaborations with other Signatories of the Agreement (e.g. on population genetics). Further research priorities include an evaluation of ecosystem vulnerability, social-ecological analyses, i.e. recognizing the close and often complex interactions between humans and nature, and recommendations for governance of the CAO. Fulfilling the 14 specific research priorities mentioned in Chapter 9 to “sufficient knowledge available” could enable the potential, future application of an Ecosystem Approach to Management for the CAO.

Acknowledgement

We are grateful to Hein Rune Skjoldal, Co-Chair of WGICA, for allowing to use the unpublished WGICA list of fish species reported from the “wider CAO area”, i.e. including the adjacent shelves surrounding the basins (version May 2019), that he compiled for WGICA.

Chapter 1. Current status, climate change and possible future fisheries

Pauline Snoeijs-Leijonmalm (SU), Hauke Flores (AWI)

1.1. Chapter summary

With the disappearance of the summer sea-ice cover and increasing territorial and commercial interests of governments and companies, the need for scientific advice on management of the Central Arctic Ocean (CAO) ecosystem, including potential fisheries, becomes urgent. Today there are no fisheries in the CAO because, except in some marginal areas for a few weeks in summer, the area is still inaccessible for fishing vessels. The *Agreement to Prevent Unregulated High Seas Fisheries in the Central Arctic Ocean*[1] (hereafter referred to as "the Agreement") aims to prevent commercial fisheries in the CAO while scientific mapping and monitoring of potential fish stocks is carried out. These research activities are now starting up with the aim to map the existing potentially exploitable fish stocks and to explore possible future sustainable fisheries in the CAO.

1.2. Background

The 3.3 million km^2 Large Marine Ecosystem (LME) around the North Pole, the Central Arctic Ocean (CAO; **Figure 1.1**), is a prominent blind spot on the map of the Earth's fish stocks. The reason for the absence of data from the CAO is obviously the difficulty of accessing this remote cold area for on-site research due to its perennial 2-3 m thick ice cover. However, observations demonstrate that the Arctic sea ice cover has been in rapid decline over the last decades, and climate models predict a further decline, with ice-free summers starting to appear already within the next few decades (Duarte et al 2012, Screen & Williamson 2017). The speed of the Arctic sea ice reduction depends largely on political decisions made (Serreze & Meier 2019). The rapid environmental changes in the CAO create new opportunities for human activities that may impact ecological and social values, including potential future commercial fisheries. Most of the CAO belongs to the "High Seas" area, i.e. being located beyond waters underlying national jurisdiction of the Arctic coastal states. Both the CAO and the Arctic High Seas consist mainly of deep abyssal plains and ridges, but the High Seas also contain a small portion (3 %) of continental shelf (**Figure 1.1,** see also **Chapter 2**). Commercial fishing does not occur in the CAO today, because the yearly ice-free time window is still locally confined and short. Furthermore, fish resources of potential commercial value have so far not been detected in the CAO.

Exploitation of newly accessible natural resources tends to precede scientific research and effective management measures, and especially internationally shared fish stocks in High Seas are prone to overexploitation (McWhinnie 2009, Christiansen et al. 2014, van Pelt et al. 2017). Therefore, a precautionary approach has recently been taken for the CAO before any exploitation of its fishery resources has taken place. In October 2018, nine countries (including the five coastal states) and the EU decided to put "science first" and abstain from engaging in commercial fishing for the next 16 years by signing the Agreement[1] (Hoag 2017, Van Pelt et al. 2017). The Agreement will enter into force when all 10 signatories have ratified it. By October 2019, the Agreement was ratified by Russia, EU, Canada, USA, Japan and South Korea, while ratification of the four other Signatories is expected in 2020.

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[1] Agreement to prevent unregulated high seas fisheries in the Central Arctic Ocean (Official Journal of the European Union L 73, 15.3.2019, pp. 3-8)

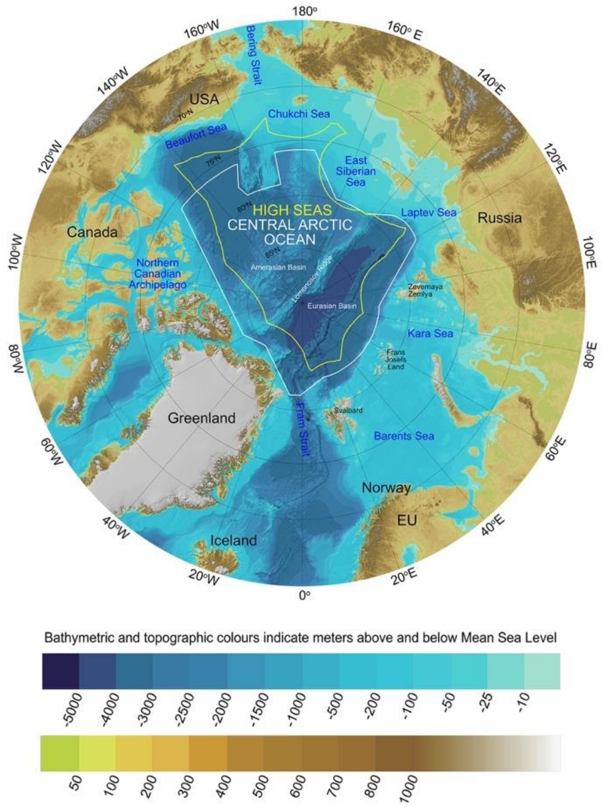

Figure 1.1. Bathymetric map of the Arctic Ocean (Jakobsson et al. 2012), showing the location of the Central Arctic Ocean (CAO) Large Marine Ecosystem as defined by the Arctic Council (PAME 2013) (white line) and the High Seas area (yellow line). The CAO is defined based on ecosystem characteristics (the oligotrophic deep basins of the Arctic Ocean and ingoing ridges) while the High Seas are defined as the area north of the Exclusive Economic Zones of the coastal states of the Arctic Ocean. The surface area of the CAO is ca. 3.3 million km^2 and that of the High Seas is ca. 2.8 million km^2.

During the preparatory phase of the Agreement, scientific advice to the Signatories was provided by five *ad-hoc* meetings of the expert group for Fishes in the Central Arctic Ocean (FiSCAO), consisting of scientists from the countries involved (FiSCAO 2017, 2018). During the First Preparatory Meeting of the Signatories to the Agreement to Prevent Unregulated High Seas Fisheries in the Central Arctic Ocean in Ottawa, Canada (29-30 May 2019) it was decided that, until all Signatories have ratified the Agreement, an interim Provisional Scientific Coordination Group (PSCG) would be installed to organize the Mapping and Monitoring Program. The first meeting of the PSCG is planned to take place in Ispra, Italy on 11-13 February 2020. In November 2019, a workshop was held in Yellowknife, Canada[2] on the processes and mechanisms to include local and indigenous knowledge into the Mapping and Monitoring program of the Agreement.

The EFICA Consortium contributes to the Mapping Program of the Agreement by joining two expeditions with the *RV Polarstern* and the *RV Oden* to the CAO in 2019-2020. Using already planned oceanographic icebreaker expeditions to the CAO is a pragmatic and relatively inexpensive approach to collect crucial fish data to fulfil the requirements of the Mapping Program and perhaps also for the future Monitoring Program.

Besides studies in the CAO itself, there are several aspects in which existing monitoring data in the gateways and shelf seas of the Arctic Ocean can be used for better understanding and predicting future developments of the fish stocks in the CAO. The two main uses of monitoring data are on (1) connectivity between fish stocks (coastal spawning areas) and (2) northward movement of fish species to the CAO with climate change. This requires a detailed review of the existing literature about northward migrations (see **Chapter 6**). Data on spawning areas needs to be extended but that can only be done if we know which species occur in the CAO. We expect possible CAO fish stocks of commercial interest to be *Boreogadus saida* (polar cod) and *Arctogadus*

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[2] Workshop on the Co-Development of Indigenous Knowledge for the Central Arctic Ocean Agreement, 13-14 November 2019, Yellowknife, Canada

glacialis (ice cod), but we cannot be sure (see **Chapters 3 and 4**). Both are single species in their genus and are referred to as *Boreogadus* and *Arctogadus*, respectively, hereafter. To understand the ecology of the potential fish stocks in the CAO and their possible future sustainable harvesting, it is also necessary to identify their role in the food web (see **Chapter 5**).

1.3. The CAO ecosystem is changing extremely fast

Global warming and ocean acidification change the habitats of the cold-adapted organisms living in the Arctic, with the risk of exterminating unique biodiversity. Human-induced emissions of greenhouse gases (primarily carbon dioxide, methane and nitrous oxide) affect the balance between energy entering and leaving the Earth's system resulting in global warming, melting of sea-ice (which increases heat absorption by the Arctic Ocean), and associated climate change (IPCC 2013). Approximately 27 % of the carbon dioxide released to the atmosphere every year is absorbed by the oceans. This keeps the atmosphere from warming as much as it otherwise would, but results in ocean acidification (i.e. decrease of seawater pH and carbonate ion concentration due to CO_2 absorption). In the Arctic region, climate change and ocean acidification take place 10-100 times faster than at any time in the past 65 million years. The Arctic region is warming faster than the rest of the globe, a process called Arctic amplification (**Figure 1.2**), caused by (1) decreased albedo when the sea ice disappears and (2) increased air and water transport from lower latitudes. Models agree on the Arctic amplification and on the loss of the summer sea ice in the CAO in this century, but disagree on both the magnitude and the exact locations where the change will be largest (IPCC 2018).

With the decrease of the summer sea-ice cover in the CAO, the only large permanently ice-covered ecosystem on Earth is vanishing. The CAO is becoming a more dynamic ecosystem with global warming, as the marginal ice zone moves further north in summer and south again in winter. The extent of both the minimum summer and winter sea ice cover has consistently been breaking negative records during the past decades: the minimum summer Arctic sea ice extent has decreased with an estimated loss rate of ~1 million km^2 (~13.2%) per decade between 1979 and 2017 (IPCC 2013, Barnhart et al. 2015, Ding et al. 2017). Simultaneously, the sea ice is also thinning (Laxon et al. 2013), with an estimated loss rate of ~3,100 km^3 (~13.5%) per decade over the period 1979 to 2017. Climate models for the Arctic region predict a further decline of the summer sea-ice cover to below 1 million km^2 within the coming 30 years, depending on which political decisions are made and implemented at a global scale (Duarte et al. 2012, Screen & Williamson 2017).

1.4. Fishable areas in the High Seas of the Arctic Ocean become accessible

Approximately 20 % of the High Seas of the Arctic Ocean consists of shallow waters of 2,000 m depth or less, while 80 % consists of deep basins (Fig. 1). The CAO is a fairly uniform ultra-oligotrophic ecosystem, i.e. with very low productivity due to low nutrient levels. Pelagic fishing would be possible in the whole area if the sea ice cover would disappear, and even bottom trawling would be possible in the larger shallow areas such as the Lomonosov, Alpha and Mendeleev Ridges. The Arctic coastal seas, except for parts of the Beaufort Sea, are situated on the continental shelves and contain most of the continental slope areas. They are influenced by land-based activities and generally nutrient-rich.

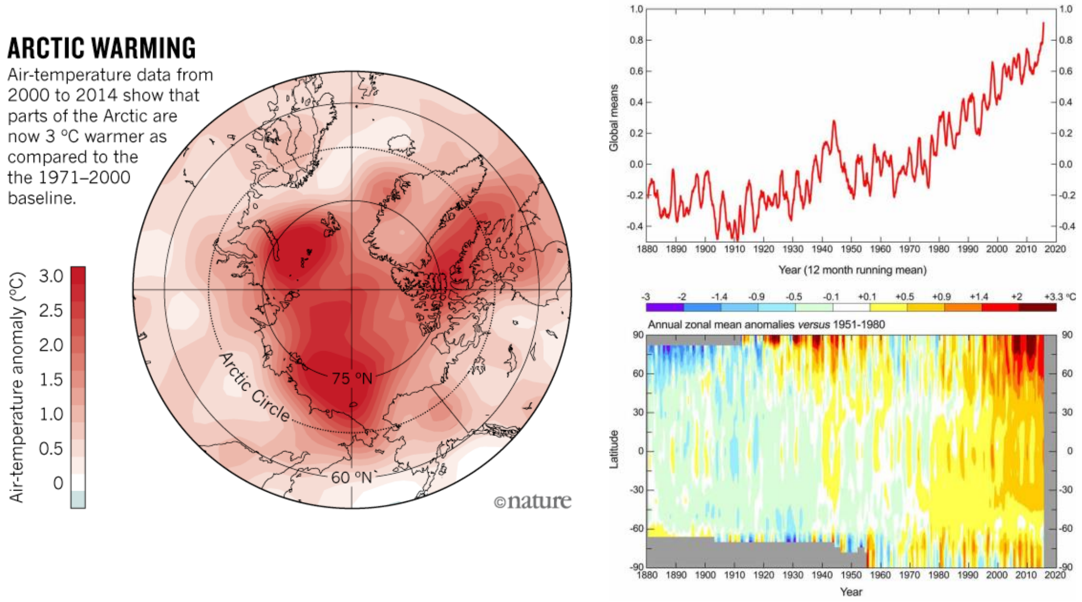


Figure 1.2. Changes in air temperature over time, showing that the Arctic region is warming faster than the rest of the globe [Nature Climate Change 7:230 (2017) and https://data.giss.nasa.gov/gistemp].

The Chukchi Plateau and the more coastal part of the Mendeleev Ridge are excluded from the CAO LME, but are still part of the High Seas. These are also the two shallow areas of the High Seas that already today are ice-free for several weeks in summer (**Figure 1.3**). The North-Pole area is predicted to become fully ice-free in summer during the coming decades, while the sea ice North of Greenland and Ellesmere Island (Canada) is expected to stay permanently ice-covered for the longest time (Screen & Williamson 2017). This means that, within the Arctic High Seas, productive areas that may be amenable for trawling are already accessible, and may soon extend into the CAO, with potential grounds for pelagic fishing along the continental slopes and within the central basin opening up during summer (Christiansen et al. 2014, Christiansen 2017). Today, the presence and future potential of commercially interesting fish stocks in these areas is unknown. Taking into account the water currents in the CAO and its distance from land, it is not expected that the CAO will become richer in nutrients with global warming (Tremblay et al. 2015). However, it is expected that even if these potentially "fishable" regions would become accessible, low levels of primary and secondary productivity would probably not be sufficient to support potential commercially relevant fish stocks.

1.5. The fish stocks in the CAO are unknown

The Arctic marine fish fauna is comprised of about 250 species, of which the majority are shelf-associated (Christiansen & Reist 2013). In shallow waters, monitoring activities with strongly varying efforts in space and time have generated an overall moderate to good knowledge of the fish stocks on the Arctic shelves (Fossheim et al. 2015, Mecklenburg & Steinke 2015, Antonov et al. 2017, Chernova 2018). Fish data from the nutrient-rich Arctic shelf seas cannot however be extrapolated to the oligotrophic (still) permanently sea ice-covered deep basins of the CAO and remote shallower areas, such as the central Lomonosov Ridge. This is due to the assumption that the carrying capacity of the oligotrophic CAO to support fish stocks is very limited (Tremblay et al. 2015), and that most species are not adapted to the deep-sea habitat.

Records of fish observations have so far been sporadic and from spatially isolated study areas, mostly using non-quantitative sampling gear from drifting sea-ice stations (Andriyashev 1957, Andriyashev et al. 1980, Tsinovsky 1980, 1981). Icebreakers with echosounders or specialized trawls have only very recently been used to detect fish in

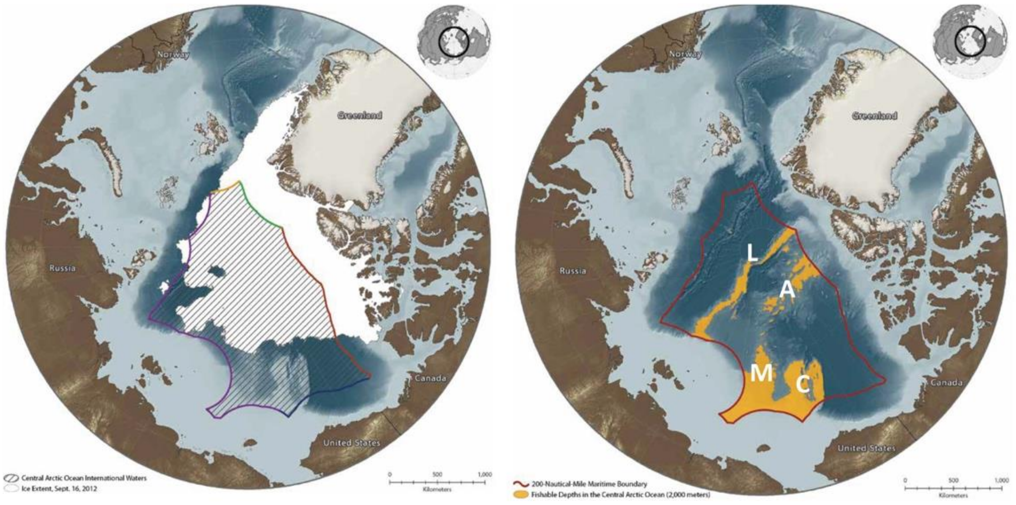


Figure 1.3. Maps of the Arctic region showing the High Seas (red line) with the minimum ice cover in summer 2012 (white area in the left map) and the shallower parts of the High Seas (yellow area in the right map) that may be more "fishable" than the deep basins. L = Lomonosov Ridge, A = Alpha Ridge, M = Mendeleev Ridge, C = Chukchi Plateau. Left: PEW map based on sea ice data from the University of Bremen SSMIS Sea Ice Data (www.iup.uni-bremen.de:8084/ssmis). Right: PEW map based on fishable depths derived from IBCAO v3 bathymetry (www.ngdc.noaa.gov/mgg/bathymetry/arctic).

the CAO (David et al. 2016, Snoeijs-Leijonmalm et al., unpublished). Hence, there is evidence of only 12 fish species occurring in the CAO (FiSCAO 2017). More fishes could potentially live there based on their known habitat, behaviour and physiological demands, but have not been documented in the CAO so far. The only two species with historically consistent records indicating a widespread distribution in the CAO are *Boreogadus saida* and *Arctogadus glacialis* that that live associated with the underside of the sea ice (Andriyashev 1957, Andriyashev et al. 1980, Tsinovsky 1980, 1981, Melnikov & Chernova 2013, David et al. 2016). On the abyssal seafloor and in the slopes of the central ridge system, there is potential for benthic fishes to occur, such as snailfishes *Liparis* spp. and eelpouts *Lycodes* spp. (see **Chapter 3**). Furthermore, lanternfishes (Myctophidae) can be expected to dwell in the mesopelagic habitat based on their distribution ranges and the connectivity of the mesopelagic layer along the Atlantic gateway (Mecklenburg et al. 2018).

Reliable data on fish stocks are generally scarce in the Arctic Ocean. A recent inventory (CAFF 2017) reported sporadic or absent monitoring of fish communities in six out of eight sectors of the Arctic Ocean. Monitoring is sporadic or absent in the Arctic Basin (CAO), the Kara-Laptev Sector, the Beaufort sector, the Hudson Complex Sector, the Davis-Baffin Sector, and the Canadian Arctic Archipelago sector. In contrast, the Atlantic Arctic (including the Barents Sea) and Pacific Arctic (including the Bering Sea) are covered by monitoring (**Figure 1.4**). In the CAO, there have been no systematic, quantitative surveys of fishes. Hence, there is no sound information about the distribution ranges, migration patterns and population sizes of any fish species living in the CAO. Therefore, there is currently no scientific basis for a sustainable management system in the CAO and the bordering shallow waters of the Arctic High Seas (FiSCAO 2018).

Figure 1.4. Map of contemporary marine fish data sources. Green squares indicate data from benthic trawl monitoring efforts, blue squares indicate data from benthic trawl surveys, while red triangles indicate data from pelagic trawl monitoring efforts. Figure from Hedges et al. in CAFF (2017).

The CAFF (2017) report presented the following conclusions with respect to (changes in) the fish populations of the Arctic Ocean and adjacent areas within the CAFF area (**Figure 1.4**):

- Pelagic and benthic fish species are important in Arctic marine ecosystems because they transfer energy to predators such as seabirds, marine mammals, as well as people.
- Northward range expansions are underway and pose unknown consequences for Arctic species and their interactions such as predation and competition.
- Fishes are affected by environmental conditions such as temperature, sea ice and salinity, and are constrained by prey availability and predator pressure, which can be influenced by climate change.
- The ecologically important polar cod declined in the Barents Sea from 2004 to 2015, potentially because of predation from Atlantic cod, a temperate-boreal species. A 2016 survey showed a notable increase in abundance, driven by an unusually high abundance of one-year-old fish.
- Indices and monitoring programs based on harvested species or that rely on fishery-related data are inherently affected by changes in stock size and exploitation rate, making them imperfect sources of information.
- Northward expanding capelin is less lipid-rich and has led to changes in seabird diet in northern Hudson Bay and may affect marine mammals negatively.
- Greenland halibut have undergone declines and subsequent recoveries over the last two decades in the northeast Atlantic.

1.6. Possible future fisheries in the CAO

Global models project an increased catch potential of potential future fisheries in the Arctic, including the CAO (Cheung et al. 2016). It has even been predicted that biodiversity of potentially exploited fish and invertebrates will increase in the CAO due to temperature-driven northwards movement of species as well as increased biological production (Jones & Cheung 2015). It is difficult, however, to evaluate the performance of these models for the CAO due to shortage of ecosystem and fisheries data.

Most Arctic fishes are not directly associated with the sea ice, but constitute an integral part of the seafloor biota. Along the shelves and slopes of the Arctic Ocean, Arctic demersal fishes may temporarily benefit from improved feeding conditions but may also be threatened by new predators, such as invading boreal fishes and mammals. Increased human activity through emerging industrial enterprises on the Arctic shelves will act as an additional stressor. *Boreogadus*, on the other hand, an abundant and prominent member of the ice-associated biota, uses sea ice as spawning substrate, shelter and feeding ground. Thus, loss of sea ice has severe and explicit costs for this focal species with profound ecological consequences (Christiansen 2017) (see **Chapter 4**).

Due to ocean warming and loss of Arctic sea ice, harvested marine fishes of boreal origin (and their fisheries) may move poleward into yet unexploited parts of the Arctic seas (Christiansen et al. 2014). Local fish stocks on the Arctic shelves are subject to commercial fisheries, e.g. in the Barents Sea (Eide et al. 2013) and Kara Sea (Antonov et al. 2017). They are also affected by changes in composition by northward movements of boreal fishes, as global warming drives changes in oceanographic conditions in the Arctic Ocean and the adjacent continental slopes (Fossheim et al. 2015; see **Chapter 6**). This may result in favourable conditions for increased biological production in waters at the northern continental shelves. However, overall production in the CAO will continue to be limited by the low amount of light and vertical stratification that is likely to become more marked with global warming (i.e. warming of the upper layer). Overall, this will reduce nutrient circulation.

The probability of fish stocks to establish themselves in the CAO depends not only on food availability, but also on the potential to provide habitat and to allow successful reproduction and recruitment of juveniles. Considering these aspects, Hollowed et al. (2013) evaluated 13 species of commercially harvested finfish and shellfish to have a moderate to high potential of range expansion into the Arctic Ocean. A high potential for expansion or range shift beyond the shelf edge into the CAO, however, appears to apply only for *Sebastes mentella* (beaked redfish), *Reinhardtius hippoglossoides* (Greenland halibut) and the pan-Arctic *Boreogadus saida* (Christiansen 2017, Haug et al. 2017).

1.7. Future management of the CAO

Increasing economic activity in the CAO is in the interest of multiple stakeholders. Hence, in addition to environmental change driven by global warming, the CAO fish stocks are potentially subject to other stressors including oil and gas exploitation, mineral extraction, shipping and tourism. Consequently, maintaining a healthy CAO ecosystem that could possibly support fisheries requires the combined management of multiple economic sectors. A future coherent international management regime for the CAO is not entirely obvious as the area is subject of geostrategic, political and economic pressures. The Agreement, including its scientific mapping and monitoring programs of potential fish stocks in the CAO, is an important first step for building an international management regime.

Chapter 2. The CAO and adjacent large marine ecosystems (LMEs)

Pauline Snoeijs-Leijonmalm (SU)

2.1. Chapter summary

The CAO is not a closed system. Its borders are defined as the continental slopes that pass over to eight large marine ecosystems (LMEs) situated on the continental shelves: the Barents Sea, Kara Sea, Laptev Sea, East Siberian Sea, Chukchi Sea, Beaufort Sea, Canadian Arctic Archipelago (or Northern Canadian Archipelago) and the Greenland Sea. To be able to model and assess the fish stocks in the CAO it is necessary to have data on connectivity with the fish stocks in the surrounding shelf seas (e.g. spawning areas, migration). From a literature search, it was concluded that the CAO is heavily under-investigated with respect to fish but also that the Agreement has raised the scientific interest in possible future fisheries and fisheries management in the area. The fish stocks of the Barents Sea are best known and adequately monitored, followed by those of the Beaufort and Chukchi Seas. Little has been published in the international literature about the fish stocks in the Russian Kara, Laptev and East Siberian Seas: knowledge probably exists but is not internationally accessible. The area north of the Canadian Arctic Archipelago and Greenland is the least accessible area of the Arctic Ocean – with the toughest sea-ice conditions – and fish-stock data for this area do not exist.

2.2. Background

The Arctic Ocean is an important part of the global climate system as a constituent of the meridional overturning and global "conveyor belt" circulation (Böhm et al. 2015, Buckley & Marshall 2016). Atlantic water – partly originating from the Gulf Stream – flows into the Arctic Ocean where it is cooled and modified and returned as cold over-flow water into the deep North Atlantic Ocean. The oceanographic processes in the North Atlantic and Arctic Oceans have received much attention in the context of climate variability and global climate change (e.g. Aagaard & Carmack 1994, Carmack & McLaughlin 2011, Mauritzen et al. 2011). The Arctic Ocean consists of four vertical layers of waters or water masses (Coachman & Barnes 1961, Rudels et al. 1991, 2004):

1. A surface layer about 50 m thick of low salinity water that is seasonally modified by sea-ice formation and melting (polar mixed layer).
2. A gradient layer (halocline) with strong increase in salinity and density between the surface layer and the next layer of Atlantic water below, located typically from about 50 to about 200 m depth (**Figure 2.1**).
3. An intermediate thick layer of relatively warm (temperature above 0 ^{o}C) Atlantic water below the halocline down to about 1,000 m.
4. Deep water of relatively uniform character (temperature between -0.5 and -1.0 ^{o}C and salinity around 34.9) filling the deep basins below the Atlantic layer.

The water circulation in the Arctic Ocean is driven by Atlantic water entering through Fram Strait and the Barents Sea, and Pacific water entering through the Bering Strait and the Chukchi Sea (Coachman & Barnes 1961, 1963, Aagaard et al. 1985, Aagaard 1989). The ratio of these two inflowing water masses is roughly 5:1. The Pacific water has lower salinity (and density) than the Atlantic water (salinity around 31-33 compared to nearly 35) and is found mainly in the upper and mid halocline layer in the Canada Basin. The Atlantic water flows into the Arctic Ocean with two main branches (Fram Strait and Barents Sea) and circulates counter-clockwise as a set of boundary currents around the slopes of the Arctic Ocean basins (Aagaard 1989, Rudels et al. 1999, 2004, Rudels & Friedrich 2000).

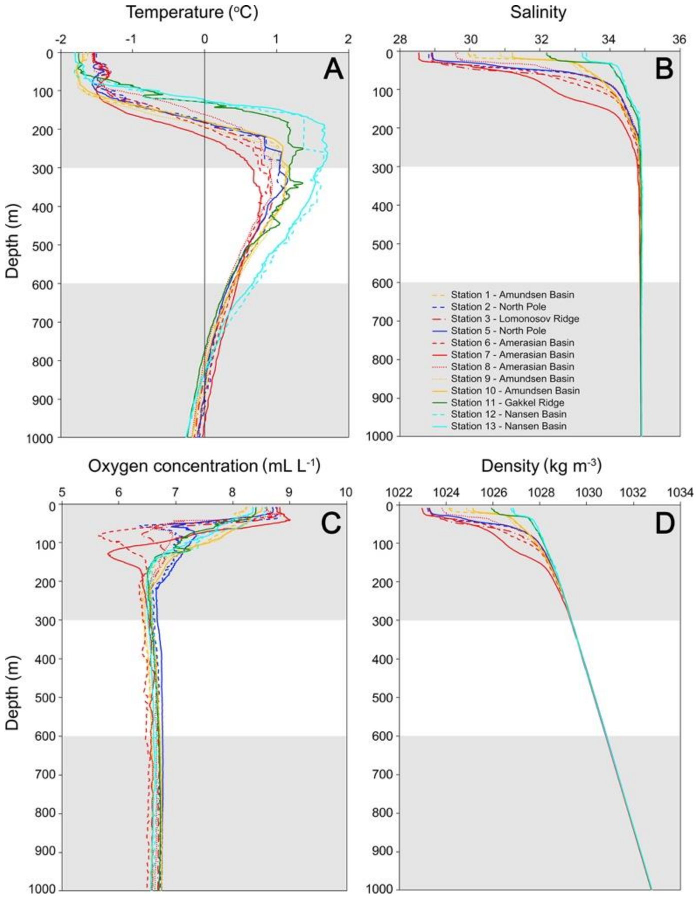


Figure 2.1. Examples of vertical profiles of oceanographic variables in the CAO. Measurements were made between 15 August and 15 September during the Arctic Ocean 2016 expedition with *RV Oden* in the upper 1000 m of the water column. (A) Water temperature. (B) Salinity. (C) Oxygen concentration. (D) Density. Figure: Snoeijs-Leijonmalm et al. (unpublished).

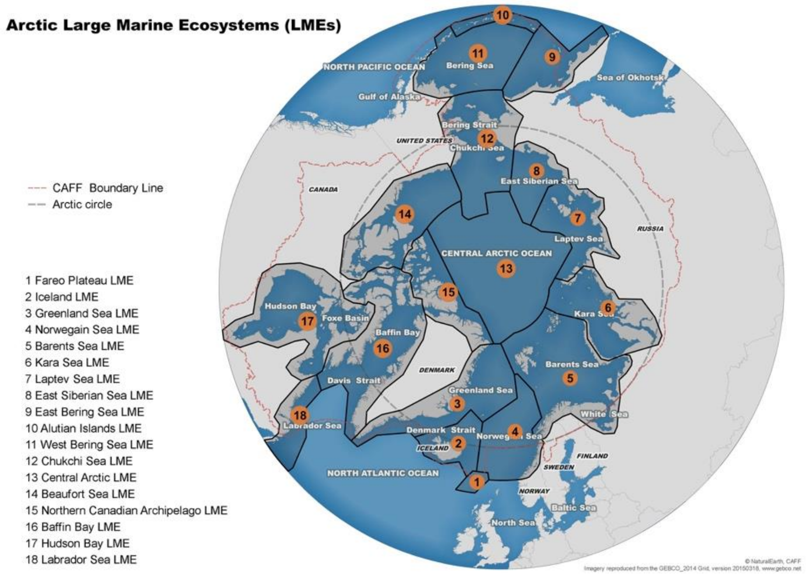


Figure 2.2. The Large Marine Ecosystems (LMEs) of the Arctic region as defined by the Arctic Council (PAME 2013).

The Arctic Council Working Group PAME has – based on ecological boundaries – defined the LMEs of the Arctic region as follows (PAME 2013; **Figure 2.2**):

The CAO is the largest of the Arctic LMEs with an area of 3.3 million km^2. It comprises essentially the deep basins of the Arctic Ocean with the Lomonosov Ridge separating the Eurasian and Amerasian basins. The key features of the CAO are the deep basins and the drifting pack ice that covers the whole area during both winter and summer, except for some of the more recent summers with especially low ice cover (**Figure 1.3**). The sea ice constitutes the habitat for cold-adapted microbial communities and a partly endemic fauna of ice amphipods and other invertebrates. Polar bears of several subpopulations move with the ice to live in the peripheral portions of the pack ice during the late summer season. This habitat is also used by two of the high arctic ice-associated gulls, *Pagophila eburnea* (ivory gull) and *Rhodostethia rosea* (Ross's gull). PAME (2013) defined the CAO LME essentially as what is left when the Arctic shelf LMEs are defined. For the LMEs on the Eurasian side – the Barents Sea, Kara Sea, Laptev Sea and East Siberian Sea – their outer boundaries include the upper slope with the Atlantic water layer and the slope currents flowing east along the continental margin. The boundaries have been approximated as straight-line segments following roughly the 1,000 m isobath. The Barents Sea includes the Yermak Plateau and also the Sofia Deep east of it. The rationale for these outer boundaries is that the slope current of Atlantic water plays important roles for the oceanography and ecology of the adjacent shelves, e.g. by transporting the copepod *Calanus hyperboreus* to deeper parts of the shelves. For the Chukchi Sea LME, the boundaries include the Chukchi Borderland with Northwind Ridge, the Chukchi Rise and the deep area in between. The northern boundary of the Beaufort Sea is along 76 °N, which approximates the average summer minimum sea-ice distribution during the recent decades. The northern boundary of the Canadian High Arctic-North Greenland LME follows the shelf edge, approximated roughly by the 200 m isobath.

The Barents Sea LME is a shelf sea with an average depth of 230 m. Atlantic water flows with two main branches into the Arctic Ocean, one branch flowing across the Barents shelf and exiting via the northern Kara Sea, and the other flowing around the shelf plateau west and north of Svalbard. This flow pattern determines the oceanographic regimes with warmer boreal and ice-free conditions in the southwestern part of the Barents Sea and cold and ice-infested conditions in the northern and eastern parts. There are distinct differences in zooplankton composition and communities, with *Calanus finmarchicus* being a dominant copepod in the Atlantic water while *Calanus glacialis* is its counterpart in Arctic water. The Barents Sea hosts large fish populations, including Atlantic cod (*Gadus morhua*), haddock (*Melanogrammus aeglefinus*), Greenland halibut (*Reinhardtius hippoglossoides*), capelin (*Mallotus villosus*) and polar cod (*Boreogadus saida*). The capelin forms a strong ecological linkage between the southern and northern Barents Sea by migrating northward in summer to feed on the zooplankton in the colder northern waters. Seasonal migrations are also characteristic for most other fish populations. The Barents Sea LME contains a large population of harp seals that whelp at the entrance to the White Sea. The LME is also home to the Barents Sea subpopulation of polar bears and two populations of walrus, the Svalbard-Franz Josef Land population and the Kara Sea-southern Barents Sea-Novaya Zemlya population. Several subpopulations of belugas (white whales) are found in the White Sea and the eastern and northern parts of the Barents Sea.

The Kara Sea LME is a shallow shelf sea (average depth 131 m). At its low-lying coasts, the estuaries of two of the major Arctic rivers, the Ob and the Yenisei, are found. These rivers discharge large volumes of freshwater that strongly influences the hydrography of the Kara Sea, resulting in extensive areas of brackish water in the summer season. The Kara Sea LME is ice-covered in winter but is generally devoid of ice in summer except for the northernmost areas. It is home to the Kara Sea subpopulation of polar bears and it contains important feeding areas for summer aggregations of belugas. The northern Kara Sea is the breeding area for the largest part of the global population of ivory gulls.

The Laptev Sea LME is situated in the central part of the Russian Arctic and has an average depth of 578 m. The northern boundary of the Laptev Sea follows along the outer slope to the Arctic Ocean basins. This area constitutes the eastern margin of the Eurasian Basins (Nansen and Amundsen) and steers the flow of Atlantic water on its way into the Arctic Ocean. A prominent feature of the Laptev Sea is the "Great Siberian Polynya" which is a system of leads and polynyas (unfrozen sea within the ice pack kept open by strong currents and/or winds), stretching from off the Taymyr Peninsula in the west to off the New Siberian Islands in the east. This polynya system provides important spring staging and feeding habitats for migratory birds, and probably also for the Laptev walrus population. The LME is also home to the Laptev Sea subpopulation of polar bears. There is possibly a migratory population of *Boreogadus* in the western part of the LME that serves as a summer feeding area for belugas of the Karskaya population wintering in the Barents Sea (Boltunov & Belikov 2002). There are several river deltas and estuaries along the southern mainland, with the Lena delta as the most prominent feature. These estuaries and deltas constitute important breeding, feeding and staging habitats for migratory birds.

The Northern Bering-Chukchi Sea LME is a shallow shelf sea with depths of 50-70 m or less extending >1,000 km from the shelf edge. The area is characterized by a persistent northward flow of water driven by higher water level in the Bering Sea than in the Arctic Ocean. The Pacific water is nutrient-rich – about three times that of North Atlantic water – and the combination of northward flow and shallow topography drives very high primary production rates in the Bering Strait region of up to 500 g C m^{-2} per year or more. This makes the region a global hot spot in terms of production, comparable to upwelling systems. The area is ice-covered in winter but ice-free in summer except for the northern part of the Chukchi Sea in cold years. *Boreogadus* is an important fish species here (Lowry & Frost 1981, De Robertis et al. 2017).

The Beaufort Sea LME has an average depth of 124 m and consists of three main components: the southern part of the deep Canada Basin, the shelf along northern Alaska and northwestern Canada, and the southwestern part of the Canadian Arctic Archipelago. Prominent features are the Mackenzie River delta and estuary and the Bathurst Polynya in the Amundsen Gulf. Primary production is relatively high due to influence of nutrient-rich Pacific water, and zooplankton residing in the deeper offshore areas provides important couplings to higher trophic levels. There is probably a large migratory population of *Boreogadus* in the eastern Beaufort Sea, which is a major summer feeding area for large numbers of bowheads and belugas from migratory populations wintering in the Bering Sea (Braham et al. 1984).

The Canadian High Arctic-North Greenland Sea is strongly influenced by heavy multi-year pack ice that is transported into the Sverdrup Basin from the Central Arctic Ocean through the openings between the northern Queen Elisabeth Islands (east of Ellesmere Island). The Nares Strait between Ellesmere Island and Greenland is one of the connections between the Arctic Ocean and Baffin Bay. The production in the LME is generally low due to the heavy ice conditions. Two polar bear subpopulations live in the area, one on each side of Ellesmere Island: the Norwegian Bay and Kane Basin subpopulations. Narwhals that summer in Smith Sound move into Kane Basin and possibly further north in the Nares Strait. Otherwise, the whales and seals of large stocks of the Baffin Bay region do not move into this ice-choked area. The coasts of northern Greenland along with Ellesmere and Axel Heiberg islands are breeding grounds for *Branta bernicla* (brent goose) and several species of high Arctic shorebirds, such as *Calidris canutus* (red knot), *Calidris alba* (sanderling), *Calidris maritima* (purple sandpiper), *Arenaria interpres* (ruddy turnstone) and *Charadrius hiaticula* (common ringed plover). These birds belong to populations that fly east to winter in western Europe or West Africa.

The Greenland Sea-East Greenland Sea consists of three distinct portions, the Greenland Sea, the western Denmark Strait, and the Southeast Greenland Shelf. The cold East Greenland Current running from the Arctic Ocean through the Fram Strait, is a prominent oceanographic feature, as is the gyre circulation within the Greenland Sea.

Most of the area is covered with sea ice in winter. *Boreogadus* is an important fish species, and the LME constitutes important breeding and feeding habitat for populations of harp and hooded seals. It is also the home of the East Greenland subpopulation of polar bears.

Physiographic provinces in the Central Arctic Ocean (CAO) and the High Seas are very similar because of the large overlap between the two areas. Both areas consist mainly of abyssal plains and ridges, but the CAO includes more rises while the High Seas includes a small area of continental shelf (Jakobsson et al. 2003). In addition to abyssal plains and ridges both areas contain submarine highlands, continental rises, continental slopes, and continental shelves, the categories perched abyssal plains, perched continental rises and isolated basins. Perched means that the province is bathymetrically elevated in relation to nearby provinces and the isolated basin was used to describe a smaller bathymetrically enclosed basin.

2.3. Summary of literature searches

To roughly summarize the existing scientific knowledge about fish and fisheries in the CAO and adjacent ecosystems, a comparison was made of the scientific publications containing the word "fish" or "fisheries" for all oceans, the Arctic Ocean (the CAO and all the shelf seas) and the CAO. These searches are full text searches and indicate any connection of the paper with fish – even if the connection is minimal, including when the words "fish" and "fisheries" occur in reference lists or author addresses.

This comparison shows that 15,081 (6.0 %) of the 249,587 scientific publications on the global ocean are connected to fish and fisheries (**Table 2.1**). Of the 15,081 scientific publications connected to fish and fisheries globally, 870 (5.8 %) mention the Barents Sea, which shows that this is a very well-studied area with respect to fish and fisheries. Another relatively well-studied area of the Arctic Ocean is the Beaufort Sea with 166 (1.1 %) papers, while the others score <0.5 %. Comparing 7,267 papers on fisheries with 15,081 papers on fish, ca. 50 % of the publications connected to fish in the global ocean deal with fisheries. For the Arctic Ocean this is ca. 30 % (indicating relatively more basic research on fish) and in the Central Arctic Ocean ca. 80 % (nearly all 18 publications are about the Agreement). Although a few publications were missed in this literature search (e.g. Melnikov & Chernova 2013), this shows that the CAO is heavily under-investigated with respect to fish but also that the Agreement has raised the scientific interest in possible future fisheries and fisheries management in the area without existing basic knowledge about the fish in the CAO ecosystem.

2.4. Summary of knowledge

A search in the Web of Science does not reflect everything that is known about fish and fisheries in the CAO and adjacent areas because data can be hidden in the "grey literature" that is not internationally accessible or as unpublished data in (national) databases (see **Chapters 3 and 4**). However, this analysis provides a good impression for which of these areas the scientific basis would be sufficient for evaluating the fish stocks from biological, management and social-ecological system (SES) perspectives.

We know very little about the CAO. After scrutinizing the 21 publications found on the CAO and the High Seas (red areas in **Table 2.1**), 16 publications were relevant for fish, fisheries or environmental protection (**Table 2.2**), but only three present original data on fish in the CAO or the High Seas. David et al. (2016) report on the sympagic (ice-associated) distribution of *Boreogadus* in the central Arctic Ocean and their association with sea-ice habitat properties. Kohlbach et al. (2017) reports a strong linkage of *Boreogadus* to sea ice algae-produced carbon evidenced by stomach content, fatty acid and stable isotope analyses. Stern & Macdonald (2005) reported on total and methyl mercury in zooplankton and fish from the Beaufort and Chukchi seas, including the

Chukchi Plateau (High Seas). The latter publication, although dealing with ecotoxicology, indirectly provides some distributional data on *Boreogadus* in the area.

The fish stocks of the Barents Sea are best known and adequately monitored, followed by those of the Beaufort and Chukchi Seas. Not much has been published in the international literature about the fish stocks in the Russian Kara, Laptev and East Siberian Seas: knowledge probably exists but is not internationally accessible. The area north of the Canadian Arctic Archipelago and Greenland is the least accessible area of the Arctic Ocean – with the toughest ice conditions – and fish-stock data for this area do not exist.

Table 2.1. The number of scientific publications found in the Web of Science Core Collection for the time span 1945-2019 with "Ocean", "Arctic Ocean", the Arctic Ocean's LMEs as well as relevant shallow areas as search criteria (All) and "fish" or "fisheries" as additional search criteria. This literature search was made on 2 July 2019. * = Sizes of the Arctic shelf seas according to PAME (2013). Note that "fisheries" also contains "fish", e.g. with the search criterion "Ocean" the search motor found 6.0 % papers with the word "fish", which includes the 2.9 % papers on fisheries, as well as papers with other words including "fish". The publications on the CAO and the High Seas are indicated in red.

Search criteria	Size (10^3 km^2)*	Average depth (m)	All	Fish	Fish (%)	Fisheries	Fisheries (%)
"Ocean"	361,132	3,688	249,587	15,081	6.0	7,267	2.9
"Arctic Ocean"	14,056	1,038	7,976	225	2.8	66	0.8
"Central Arctic Ocean"	3,281		623	18	2.9	14	2.2
"Lomonosov Ridge"			357	2	0.8	0	0.0
"Alpha Ridge"			131	0	0.0	0	0.0
"Mendeleev Ridge"			108	0	0.0	0	0.0
"Chukchi Plateau"			47	1	2.1	0	0.0
"Barents Sea"	2,010	230	5,476	870	15.9	397	7.2
"Kara Sea"	1,000	131	1,060	18	1.7	3	0.3
"Laptev Sea"	920	578	933	10	1.1	0	0.0
"East Siberian Sea"	640	58	250	6	2.4	0	0.0
"Chukchi Sea"	620	80	2,012	71	3.5	19	0.9
"Beaufort Sea"	1,110	124	2,530	166	6.6	32	1.3
"Canadian Arctic Archipelago"	600		679	9	1.3	0	0.0
"Greenland Sea"	1,200	1,444	1,692	42	2.5	7	0.4

Table 2.2. The 21 scientific publications on the Central Arctic Ocean related to fish or fisheries found in the Web of Science Core Collection for the time span 1945-2019 *cf.* **Table 2.1**. Five of the papers were not relevant for fish, fisheries or environmental protection in the CAO. The three publications in red are the only papers that present original data on (sympagic) fish in the CAO (David et al. 2016, Kohlbach et al. 2017) or the Chukchi Plateau in the High Seas (Stern & Macdonald 2005).

Relevant	Year	Scientific paper	Citations
Yes	2018	Niiranen S, et al. (2018) Global connectivity and cross-scale interactions create uncertainty for Blue Growth of Arctic fisheries. Marine Policy 87:321–330	3
Yes	2018	Zou L, Huntington HP (2018) Implications of the Convention on the Conservation and Management of Pollock Resources in the Central Bering Sea for the management of fisheries in the Central Arctic Ocean. Marine Policy 88:132–138	2
Yes	2018	Manero SA (2018) The Arctic Environmental Protection and the Agenda 2030. Actualidad Jurídica Ambiental, ISSN-e 1989-5666, No. 77, pp. 4-34	0
Yes	2018	Bertelsen RG (2018) The International Political Systemic Context of Arctic Marine Resource Governance. Arctic Marine Resource Governance and Development 3:17 [abstract]	0
Yes	2018	Rayfuse R (2018) Regulating fisheries in the Central Arctic Ocean: Much ado about nothing? In: Vestergaard N, et al. (Eds) Arctic Marine Resource Governance and Development, Springer Nature. pp. 35–51	0
Yes	2018	Papastavridis E (2018) Fisheries Enforcement on the High Seas of the Arctic Ocean: Gaps, Solutions and the Potential Contribution of the European Union and Its Member States. International Journal of Marine and Coastal Law 33:324–360	0
Yes	2017	Haug T, et al. (2017) Future harvest of living resources in the Arctic Ocean north of the Nordic and Barents Seas: A review of possibilities and constraints. Fisheries Research 188:38–57	24
Yes	2017	Kohlbach D, et al. (2017) Strong linkage of polar cod (*Boreogadus saida*) to sea ice algae-produced carbon: Evidence from stomach content, fatty acid and stable isotope analyses. Progress in Oceanography 152:62–74	16
Yes	2017	Van Pelt TI, et al. (2017) The missing middle: Central Arctic Ocean gaps in fishery research and science coordination. Marine Policy 85:79–86	3
Yes	2017	Norris AJ, McKinley P (2017) The central Arctic Ocean-preventing another tragedy of the commons. Polar Record 53:43–51	2
Yes	2016	David C, et al. (2016) Under-ice distribution of polar cod *Boreogadus saida* in the central Arctic Ocean and their association with sea-ice habitat properties. Polar Biology 39:981-994	21
Yes	2016	Pan M, Huntington HP (2016) A precautionary approach to fisheries in the Central Arctic Ocean: Policy, science, and China. Marine Policy 63:153–157	10
Yes	2016	Shephard GE, et al. (2016) Assessing the added value of the recent declaration on unregulated fishing for sustainable governance of the central Arctic Ocean. Marine Policy 66:50-57	5
Yes	2016	Zagorskii AV (2016) International Cooperation in the Arctic. Mirovaya Ekonomika i Mezhdunarodnye Otnosheniya 60:104–112	1
Yes	2011	Wassmann P, et al. (2011) Footprints of climate change in the Arctic marine ecosystem. Global Change Biology 17:1235–1249	332
Yes	2005	Stern GA, Macdonald RW (2005) Biogeographic provinces of total and methyl mercury in zooplankton and fish from the Beaufort and Chukchi seas: Results from the SHEBA drift. Environmental Science and Technology 39:4707–4713	39
No	2018	Luo W, et al. (2018) Microbial eukaryotic diversity with emphasis on picoprasinophytes under the sea ice of the central Arctic Ocean in summer. Current Science 115:1709–1713	0
No	2017	Ramirez-Llodra E, et al. (2017) Deep, diverse and definitely different: unique attributes of the world's largest ecosystem. Biogeosciences 7:2851–2899	240
No	2017	Tachikawa K, et al. (2017) The large-scale evolution of neodymium isotopic composition in the global modern and Holocene ocean revealed from seawater and archive data. Chemical Geology 457:131–148	15
No	2009	Gleason JD, et al. (2009) Early to middle Eocene history of the Arctic Ocean from Nd-Sr isotopes in fossil fish debris, Lomonosov Ridge. Paleoceanography 24:PA2215	18
No	2008	Waddell LM, Moore TC (2008) Salinity of the Eocene Arctic Ocean from oxygen isotope analysis of fish bone carbonate. Paleoceanography 23:PA1S12	36

2.5. Critical gap analysis

Table 2.3. Critical gap analysis for variables relevant for ecosystem analyses and climate change impacts in the CAO. Estimate of severity of the knowledge gap: 0 = no knowledge, 1 = serious lack of knowledge, 2 = insufficient knowledge, 3 = sufficient knowledge available for the purpose indicated in column 2.

Variable	Why the variable is necessary to evaluate possibilities for future fisheries	Estimate of severity of the knowledge gap	What data needs to be collected to decrease the gap?
Oceanography of the CAO	Environmental conditions for modelling and assessment of fish stocks in the CAO	2-3	The oceanography of the Arctic Ocean is relatively well-known but it is necessary to measure temperature, salinity, oxygen, etc. simultaneously with a scientific survey of the food web
Bottom topography of the CAO	Environmental conditions for modelling and assessment of fish stocks in the CAO	2-3	An International Bathymetric Chart of the Arctic Ocean exists (Jakobsson et al. 2012) and is routinely being refined by seagoing expeditions
Ice cover dynamics	Environmental conditions for modelling and assessment of fish stocks in the CAO	3	This is very well studied in a longer time perspective, e.g. NASA
Winter conditions in the CAO	Seasonality of environmental and biotic factors for modelling and assessment of fish stocks in the CAO	1	Winter conditions are generally less known than summer conditions in all fields of science
Effects of disappearance of sea-ice on the sympagic, marine pelagic and benthic food webs in the CAO	Food-web interactions in a changing environment for modelling and assessment of fish stocks in the CAO	1	Comparative studies of the diversity and functioning of the food webs between ice-covered and non-ice-covered waters in the CAO
Fish stocks in the Arctic Ocean LMEs			
Fish stocks in the CAO	The minimum basic data for modelling and assessment of fish stocks in the CAO	1	Acoustics in combination with oceanography and scientific surveys of the pelagic, sympagic and benthic food webs
Fish stocks in the Barents Sea	Connectivity with the fish stocks in the CAO for modelling and assessment of fish stocks in the CAO	3	The fish stocks are very well known and monitored
Fish stocks in the Bering, Beaufort and Chukchi Seas Sea	Connectivity with the fish stocks in the CAO for modelling and assessment of fish stocks in the CAO	2	The fish stocks are known and monitored except for the outer areas of the deep ice-covered Beaufort Sea and the Chukchi Plateau
Fish stocks in the Kara, Laptev and East Siberian Seas	Connectivity with the fish stocks in the CAO for modelling and assessment of fish stocks in the CAO	1	The fish stocks are known and monitored but the information is not internationally accessible –cooperation with Russian scientists should be stimulated through the Agreement
Fish stocks north of the Canadian Arctic Archipelago and Greenland	Connectivity with the fish stocks in the CAO for modelling and assessment of fish stocks in the CAO	1	The fish stocks are not known and not monitored because the area is basically inaccessible (extremely tough ice conditions)

Chapter 3. Pelagic and benthic fish: species, population dynamics, distribution

Pauline Snoeijs-Leijonmalm (SU), Filip Volckaert (KU Leuven)

3.1. Chapter summary

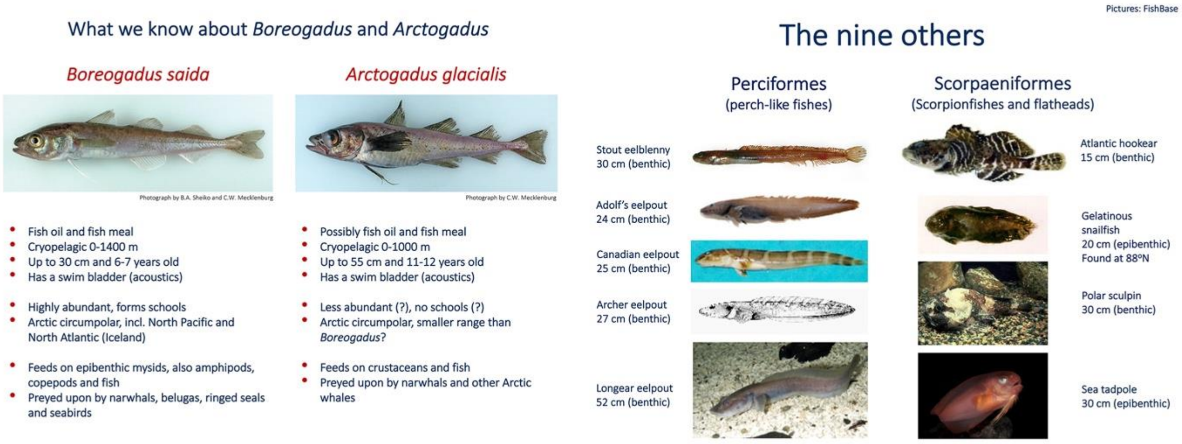
Very little is known about the pelagic and benthic fish in the CAO. The cryopelagic gadoids *Boreogadus saida* and *Arctogadus glacialis*, both Arctic endemics, are the two species we would expect to find in significant abundances in the pelagic zone of the CAO. *Boreogadus* is a key species in the Arctic marine shelf ecosystems, serving as important trophic link between plankton and apex predators, and has previously been harvested for fish oil and fish meal. It is often the main food source for many Arctic marine mammals, including beluga whales and ringed seals. *Arctogadus* is a less abundant species. It is necessary to combine hydroacoustic studies with scientific surveys of the pelagic food web in this mesopelagic scattering layer. A highly commercial bentho-pelagic species, the Greenland halibut *Reinhardtius hippoglossoides*, has been observed in the CAO only once at 75 °N (1,665 km south of the North Pole). The other nine species recorded in the CAO are nine benthic species without any known commercial value.

3.2. Background

From an assessment of published data and data in fisheries databases compiled by the FiSCAO Expert Group in its fourth report, and the gap analysis in **Chapter 2** of this report, it is clear that very little data exists on fish in the CAO and the Arctic High Seas (FiSCAO 2017). The FiSCAO Expert Group presented an inventory of all fish species recorded until 2016 in all Arctic LMEs (CAO and shelf seas). In addition to *Boreogadus* and *Arctogadus* they found that nine fish species of no commercial interest had been detected in the CAO (**Figure 3.1**). The 12th and last species recorded from the CAO is the Greenland halibut *Reinhardtius hippoglossoides*, which is a highly commercial bentho-pelagic species, but it was found only once in the CAO at 75 °N (1,665 km south of the North Pole).

Based on the few observations in the CAO, *Boreogadus* and *Arctogadus* (**Figure 3.1**) are the two species we expect to find in significant abundances in the pelagic zone of the High Seas of the CAO. However, they may occur mixed with other fishes. For example, Gjøsæter et al. (2017) reported *Boreogadus* to occur together with *Arctozenus risso* (spotted barracudina) and *Sebastes mentella* (beaked redfish), as well as the lanternfishes *Benthosema glaciale* (glacier lanternfish) and *Lampanyctus macdonaldi* (rakery beaconlamp) from an acoustic scattering layer in the Svalbard area just outside the CAO. Early studies from Soviet drifting ice stations reported *Boreogadus*, *Arctogadus* and the snail fishes *Paraliparis bathybius* (black seasnail) and *Lycodes frigidus* (glacial eelpout) from the CAO (Andriyashev et al. 1980).

Boreogadus has been exploited in the Barents Sea for the production of fish oil and fish meal. The Soviet and Russian fishing fleets have fished this species since 1966, with peak catches (332,000 tonnes) in 1971. Norway only fished *Boreogadus* in 1969-1971, but to a much lesser extent (16,000 tonnes in 1971; Hop & Gjøsæter 2013). *Arctogadus* has not been commercially exploited, probably because no schools have been observed, but it could deliver the same products as *Boreogadus* (e.g. fish oil and fish meal). The two species are closely related cod fishes, but *Arctogadus* becomes older and larger than *Boreogadus* and stable isotope analyses place *Arctogadus* slightly higher up in the food web in the areas adjacent to the High Seas of the CAO (Christiansen et al. 2012). Juvenile *Boreogadus* are cold-adapted (Kunz et al. 2016), live closely associated with sea ice and significantly depend on ice-associated resources (Kohlbach et al. 2017; see **Chapter 4**). This makes them particularly vulnerable to ocean warming and sea ice decline, along with other human-induced stressors, e.g. microplastic pollution (Kühn et al. 2018, Peeken et al. 2018).



What we know about *Boreogadus* and *Arctogadus*

Boreogadus saida

Photograph by B.A. Sheiko and C.W. Mecklenburg

- Fish oil and fish meal
- Cryopelagic 0-1400 m
- Up to 30 cm and 6-7 years old
- Has a swim bladder (acoustics)

- Highly abundant, forms schools
- Arctic circumpolar, incl. North Pacific and North Atlantic (Iceland)

- Feeds on epibenthic mysids, also amphipods, copepods and fish
- Preyed upon by narwhals, belugas, ringed seals and seabirds

Arctogadus glacialis

Photograph by C.W. Mecklenburg

- Possibly fish oil and fish meal
- Cryopelagic 0-1000 m
- Up to 55 cm and 11-12 years old
- Has a swim bladder (acoustics)

- Less abundant (?), no schools (?)
- Arctic circumpolar, smaller range than *Boreogadus*?

- Feeds on crustaceans and fish
- Preyed upon by narwhals and other Arctic whales

Pictures: FishBase

The nine others

Figure 3.1. Fish species recorded in the CAO according to FiSCAO (2017). *Boreogadus saida* and *Arctogadus glacialis* are the two fish species recorded in the CAO that may be of commercial interest. Their distributions in the High Seas of the CAO are largely unknown. Besides *Boreogadus* and *Arctogadus*, nine benthic fish species of no commercial interest (www.fishbase.org) have been recorded in the CAO, but only one (gelatinous snailfish) north of 77 °N.

3.3. Summary of literature searches

A literature search focusing on *Boreogadus* and *Arctogadus* was carried out (**Table 3.1**). Scientific publications were identified in the Web of Science (WoS) with the geographic search criteria "Ocean", "Arctic Ocean" and "Central Arctic Ocean", as well as relevant geographic areas (**Figure 1.1**) and "fish", "*Boreogadus*" or "*Arctogadus*" as additional search criteria. After checking the identified papers on the CAO and High Seas for overlapping papers and relevant contents, 17 papers on fish, eight on *Boreogadus* and one on *Arctogadus* remained. In addition, 17 relevant papers on *Boreogadus* and 12 on *Arctogadus* that were not identified by the WoS by the (full text) key words or absent from the WoS, were found by Google. After compensation for overlapping papers identified by "fish", "*Boreogadus*" or "*Arctogadus*", 40 papers were left. These 40 papers can be divided into four categories:

1. **Papers presenting original data on sympagic fish distribution in the CAO** (Andriyashev et al. 1957, Andriyashev et al. 1980, Tsinovsky 1980, 1981, Gradinger & Bluhm 2004, Melnikov & Chernova 2013, David et al. 2015, 2016, Kohlbach et al. 2017, Kühn et al. 2018).
2. **Papers presenting original data on pelagic fish distribution at or close to the Chukchi Plateau in the High Seas** (Walters 1961, Tsinovsky 1981, Bluhm et al. 2005, Stern & Macdonald 2005, Crawford et al. 2012, Mecklenburg et al. 2014, Vestfals et al. 2019).
3. **Review papers including data on pelagic fish distributions in the Arctic Ocean** (Melnikov 1980, Aschan et al. 2009, Chernova 2011, Mecklenburg et al. 2011, Christiansen 2012, Christiansen & Reist 2013, Hop & Gjøsæter 2013, Berge et al. 2015, Bluhm et al. 2015, Mecklenburg & Steinke 2015, Mueter et al. 2016, Bouchard et al. 2017).
4. **Papers on policy and management** (Pan & Huntington 2016, Shephard et al. 2016, Edwards & Evans 2017, Haug et al. 2017, Norris & McKinley 2017, Van Pelt et al. 2017, Harris et al. 2018, Landriault 2018, Niiranen et al. 2018, Papastavridis 2018, Zou & Huntington HP 2018).

Table 3.1. The number of scientific publications found in the Web of Science Core Collection for the time span 1945-2019 with relevant geographical areas as search criteria (All) and "fish", "*Boreogadus*" or "*Arctogadus*" as additional search criteria. This literature search was made on 2nd July 2019. Additional papers = papers and reports in our personal libraries that were not identified by the WoS by the key words or absent from the WoS.

Search criteria		In the Web of Science data base (WoS)						Additional papers	
	All	Fish	Fish	*Boreogadus*	*Boreogadus*	*Arctogadus*	*Arctogadus*	*Boreogadus*	*Arctogadus*
None	67,457,677	405,184		394		35		98	86
"Ocean"	249,587	15,081		70		8			
"Arctic Ocean"	7,976	223		39		7			
"Central Arctic Ocean"	623	18	18	5	9	0	1	17	12
"Amundsen Basin"	87	1		2		0			
"Nansen Basin"	171	1		2		0			
"Canada Basin"	735	10		8		1			
"Gakkel Ridge"	228	1		0		0			
"Lomonosov Ridge"	358	3		0		0			
"Alpha Ridge"	131	0		0		0			
"Mendeleev Ridge"	108	0		0		0			
"Chukchi Plateau"	47	1		1		0			
"Chukchi Borderland"	55	2		1		1			
"Chukchi rise"	8	0		0		0			
"Beaufort Gyre"	252	1		0		0			
"Arctic" and "High Seas"	39	13		1		0			
"Barents Sea"	5,476	870		83		2			
"Kara Sea"	1,060	18		3		0			
"Laptev Sea"	933	10		7		1			
"East Siberian Sea"	250	6		1		0			
"Chukchi Sea"	2,012	71		35		1			
"Beaufort Sea"	2,530	166		87		5			
"Canadian Arctic Archipelago"	679	9		3		0			
"Greenland Sea"	1,692	42		18		1			

3.4. Summary of knowledge

Preliminary hydroacoustic observations suggest the occurrence of a deep scattering layer in the "warm" (0.4-1.2 °C) Atlantic water masses of the ice-covered CAO at 300-600 m (Snoeijs-Leijonmalm et al., unpublished). The acoustic backscatter energy is very low and could originate from low abundances of the small Arctic gadoid fishes *Boreogadus* and *Arctogadus*. However, physonect siphonophores (Class Hydrozoa, Phylum Cnidaria) may also contribute to the backscatter, thus sampling organisms from this layer is mandatory to be able to draw conclusions about fish abundance.

Data from the Beaufort Sea shows *Boreogadus* to be vertically segregated by size in all months, with juveniles in the epipelagic (<100 m) layer and older *Boreogadus* in the Atlantic layer along the slopes of the Beaufort Sea at 200-500 m depth (Parker-Stetter et al. 2011, Benoit et al. 2014, Geoffroy et al. 2016). It has been hypothesized that early hatching (already in January) enables the juvenile fish to reach a minimum size and the capacity to avoid predation before they join their cannibalistic congeners in the mesopelagic Atlantic layer in the Arctic shelf seas (Bouchard & Fortier 2011). This strategy might be the same in the CAO with juveniles associated with sea ice (Gradinger & Bluhm 2004, Melnikov & Chernova 2013, David et al. 2016) and adults deeper down.

Boreogadus is a key species in the Arctic marine shelf ecosystems, serving as an important trophic link between plankton and apex predators (Hop & Gjøsæter 2013, Christiansen & Reist 2013, Mueter et al. 2016, Chernova 2018). *Boreogadus* are often the main food source for many Arctic marine mammals, including beluga whales (Loseto et al. 2009, Hauser et al. 2015) and ringed seals (Crawford et al. 2015). *Arctogadus* is less abundant and it seems to be primarily associated with the Arctic fjords and shelves (Aschan et al. 2009). The two species are taxonomically distinguished by simple phenotypic features for adults (Christiansen 2012) and genetic markers for the larval stages (Madsen et al. 2009).

Early records of *Boreogadus* and *Arctogadus* in the CAO originate from the drifting ice station North Pole-16 (NP-16) during the winter period 1968–1969 (Andriyashev et al. 1980). The species was found to occur in association with the sea ice cover and in the pelagic zone – but only down to a depth of 25 m – by fishing with lines and nets. Andriyashev et al. (1980) reports length measurements of ca. 200 fish specimens (176 *Boreogadus* and 32 *Arctogadus*) and weight and age for 19 *Arctogadus*, but reports high abundances of up to 1,600 individuals observed on one day in the upper sub-ice water layer. Walters (1961) reported the occurrence of *Arctogadus* from the American drifting ice station "Station Charlie" in the High Seas near the Chukchi Plateau using bottom dredging and seismic blasts. Altogether, 35 specimens of 12-24 cm standard length were collected from two seismic blasts on 10 and 21 December 1959, and between 21 December and 3 January 50-70 individuals were caught daily in this way. *Arctogadus* was not obtained in summer, and in winter only when Station Charlie was in the neighbourhood of the Chukchi rise, and it was concluded that the fish was probably not ice-associated but truly pelagic. Furthermore, it was suggested that schools of A*rctogadus* undertake a feeding migration in mid-winter across the shallow waters of the Chukchi Plateau. All investigated specimens had their stomachs full of small crustaceans and they had large fat deposits in their body cavities. Walters (1961) also reported two non-commercial benthic fish, the glacial eelpout *Lycodes frigidus* and the sea tadpole *Careproctus reinhardti* (**Figure 3.1**).

The genetic diversity and connectivity of Arctic fish populations, regardless of being exploited or not, represents important information to understand biogeographical patterns, population structure and connectivity, and to support sustainable management. In addition to the information on *Boreogadus* and *Arctogadus* provided in **Chapter 4**, we performed a literature search focusing on the population genetics of the ten additional high sea fish species that have been reported to inhabit the CAO (FiSCAO 2017): the gelatinous seasnail *Liparis fabricii*, Adolf's eelpout *Lycodes adolfi*, longear eelpout *Lycodes seminudus*, Archer eelpout *Lycodes saggittarius*, Canadian eelpout *Lycodes polaris*, Atlantic hookear sculpin *Artediellus atlanticus*, Polar sculpin *Cottunculus microps*, sea tadpole *Careproctus reinhardti*, stout eelblenny *Anisarchus medius* (**Figure 3.1**) and the commercially exploited Greenland halibut *Reinhardtius hippoglossoides*. We found only few references, except for Greenland halibut. Mitochondrial DNA did not reveal any genetic structure across the geographical range of this species (Vis et al. 1997). These data would suggest that there is sufficient mixing of Greenland halibut among sites in the North Atlantic generally, to prevent the development or maintenance of genetically independent stocks. However, nine DNA microsatellites detected partially isolated populations in the North Atlantic Ocean, which was attributed to drift of eggs and larvae from the spawning grounds (Knutsen et al. 2007). In a more recent study (Westgaard et al. 2017), 96 single nucleotide polymorphic (SNP) markers detected weak but significant population structure separating a western Atlantic population and an eastern Atlantic population. Again, this was attributed to egg and larval drift and/or migratory behaviour among populations of Greenland halibut.

In the absence of complementary biological information, biophysical modelling of dispersal is likely to be highly informative, as proven in fish (Barbut et al. 2019) and meroplankton (Le Goff et al. 2017). The warming of Arctic waters is driving a major shift in the composition of the fish community through the northward extension of southern species (Fossheim et al. 2015, Andrews et al. 2019, see **Chapter 6**). Pressure on the polar fish populations will lead to major changes in the population structure. Genetic monitoring in addition to ecological monitoring can provide the necessary information for informed management decisions. Although we have been focussing on genetic methods, integrated genetic, microchemical and biophysical/niche modelling is recommended to understand stock structure, connectivity and distribution in an environmental context (e.g. Selkoe et al. 2016).

3.5. Critical gap analysis

Table 3.2. Critical gap analysis for variables relevant for species, population dynamics and distribution of pelagic and benthic fish in the CAO. Estimate of severity of the knowledge gap: 0 = no knowledge, 1 = serious lack of knowledge, 2 = insufficient knowledge, 3 = sufficient knowledge available for the purpose indicated in column 2.

Variable	Why the variable is necessary to evaluate possibilities for potential future fisheries	Estimate of severity of the knowledge gap	What data needs to be collected to decrease the gap?
Pelagic fish data in the CAO (species, population structure, geographical distribution)	The minimum basic data for modelling and assessment of fish stocks in the CAO	0	Acoustics in combination with oceanography and scientific surveys of the pelagic food web across the CAO
Benthic fish data in the CAO (species, population structure, geographical distribution)	The minimum basic data for modelling and assessment of fish stocks in the CAO	0	Scientific surveys of the benthic food web across the CAO
Food sources	Food-web interactions in a permanently ice-covered sea for modelling and assessment of fish stocks in the CAO	0	Comparative studies of the diversity and functioning of the pelagic and benthic food webs in the CAO
Predators	Food-web interactions in a permanently ice-covered sea for modelling and assessment of fish stocks in the CAO	1	Comparative studies of the diversity and functioning of the pelagic and benthic food webs in the CAO
Effects of disappearance of sea-ice on the pelagic and benthic food webs in the CAO	Food-web interactions in a changing environment for modelling and assessment of fish stocks in the CAO	1	Comparative studies of the diversity and functioning of the pelagic and benthic food webs between ice-covered and non-ice-covered waters in the CAO

Chapter 4. Sympagic fish: species, population dynamics, distribution

Hauke Flores (AWI), Filip Volckaert (KU Leuven)

4.1. Chapter summary

Boreogadus saida is the most abundant fish in the shelf/slope regions of the Arctic Ocean. The juvenile individuals of this species are associated with sea ice ("sympagic"), including in the CAO, which they use as a foraging ground and a shelter from predators. Besides *Boreogadus*, *Arctogadus* also associates with sea ice during the first part of its life cycle. *Arctogadus* populations seem to be centered in the region north of Greenland and the Canadian Arctic Archipelago. Their distribution in the CAO is unknown. There is widespread evidence that sympagic *Boreogadus* occur throughout the CAO, but data are scattered in space and time, and there is almost no quantitative information. A first systematic under-ice survey in the Eurasian Basin found evidence that the Transpolar Drift transports young *Boreogadu*s from hatching areas on the Siberian shelf across the CAO. This trans-polar gene flow is supported by population genetic analyses. Based on the paucity of quantitative information on sympagic *Boreogadus* available to date, their total population size in the CAO remains undetermined. We also have limited knowledge about the connection between sympagic and mesopelagic populations, vertical migrations, and winter survival.

4.2. Background

Sea ice constitutes a highly dynamic and multi-facetted habitat for fishes. A part of the sea-ice habitat is attached to the coast and is called "landfast sea ice", or "fast ice". It offers a highly stable environment as long as it persists. Most of the Arctic sea ice, however, consists of pack-ice drifting freely on the ocean surface. The Arctic pack-ice is highly dynamic, as it moves with the ocean currents and is deformed, creating a highly heterogeneous icescape of pressure ridges, open leads and flat ice floes. An increasingly large part of the Arctic sea ice melts during summer (first-year ice: FYI), adding a progressively seasonal component to the dynamics of the sea-icescape. Ice floes that survive the melting season can persist in the Arctic Ocean for several years and are called multi-year ice (MYI). The proportion of MYI in Arctic sea ice has been decreasing rapidly during the past decades (Meier et al. 2014). Polar fishes use sea ice as a protection from predators, as a foraging ground, and as a nursery habitat for eggs, larvae and juveniles (Andriyashev et al. 1980, Lønne & Gulliksen 1989, Bouchard et al. 2016, Nahrgang et al. 2016, Kohlbach et al. 2017). The use of the sea-ice habitat by these ice-associated ("sympagic") fishes can be expected to vary with the changing dynamics of its physical properties, e.g. topography, drift trajectories or proportion of MYI versus FYI.

In the Arctic Ocean, two closely related fish species have been assumed to employ a sympagic mode of life at least during parts of their life cycle: *Boreogadus* and *Arctogadus. Boreogadus* is assumed to be the most abundant fish in the CAO and in the bordering shelf/slope regions belonging to the Arctic High Seas. The juvenile (1-2 years old) individuals of this species are often associated with sea ice, which they use as a foraging ground and as a shelter from predators (Lønne & Gulliksen 1989, Gradinger & Bluhm 2004). Knowledge on the abundance and distribution of *Boreogadus* under Arctic sea ice has predominantly been anecdotal, non-quantitative, and spatially and temporally limited in the past (Walters 1961, Andriyashev 1957, Melnikov & Chernova 2013). Only recently, a first quantitative under-ice survey in the Eurasian Basin estimated a minimum biomass of fish dwelling in the ice-water interface layer of about 15 kg km^{-2} (David et al. 2016). The Transpolar Drift probably transports young *Boreogadus* from hatching areas on the Siberian shelf across the CAO to the Svalbard / Barents Sea region and northern

Greenland (David et al. 2016). The *Arctogadus* has a similar circumpolar distribution as *Boreogadus*, but there is no evidence of sympagic *Arctogadus* from the European Sector of the Arctic Ocean. Due to its overall lower abundance, this species has received far less attention than *Boreogadus*. *Arctogadu*s is generally considered a rather benthic species, but a few observations indicate also a sympagic mode of life for the early life stages (Walters 1961, Tsinovsky 1980, Bouchard et al. 2016).

Published knowledge on sympagic fishes in the Arctic Ocean dates back to the 1940s (Andriyashev 1957). However, information on sympagic *Boreogadus* and *Arctogadus* has been discontinuous in time and scattered in space, and quantitative information is rare. Here we review the available information following a scrutinized approach using multiple databases, and including both peer-reviewed scientific articles, and reports. Following this inventory, we perform a gap analysis focusing on the taxonomic, spatial and temporal coverage of the published data in order to identify priorities for future research directed towards a stock assessment of sympagic fishes in the Arctic High Seas, and an assessment of the future prospect of these stocks under climate change scenarios.

4.3. Summary of literature searches

We conducted searches in the public research databases Web of Science, Scopus, Google Scholar, and Publications.europa.eu. With the search terms used, we aimed to limit the result to publications addressing Arctic ice-associated fishes, but at the same time to minimize the risk that relevant publications were missed. All queries comprised the terms "Arctic Ocean", "fish", and "sea ice", but we varied the search terms according to the different search syntaxes in the different databases. The scientific research databases Web of Science and Scopus allowed for the most precise expression of the queries. Here, we included also the two presumably sympagic fish genera "*Arctogadus*" and "*Boreogadus*" in combination with the term "sea ice". The search comprised the entire temporal coverage of the four databases. We generally allowed the databases to return all types of publications. Only in Publications.europa.eu we excluded legal documents.

The output of the different databases was quite variable in terms of number of discovered publications, publication type, and temporal coverage. The two scientific databases Web of Science and Scopus yielded similar amounts of publications (126 and 157, respectively) and covered a similar time period (1992-2019 and 1986-2019, respectively; **Table 4.1**). The publication type composition was clearly dominated by original research articles. Google Scholar yielded a considerably lower number of publications (73), but covered a longer time period in the past (1971-2019; **Table 4.1**). The European database Publications.europa.eu returned the largest number of publications (180) and covered a similar time period as Web of Science and Scopus (**Table 4.1**). The publication type composition was clearly dominated by reports directed at policy and resource management. Overall, the vast majority of publications identified by the four databases did not contain specific data about sympagic fishes. Only 23 publications contain such specific information (**Table 4.2**).

4.4. Summary of knowledge

The inventory of the published literature on sympagic fishes in the Arctic Ocean was based on the outcome of the database queries, but was extended by historical records from earlier years not covered by the four databases. The earliest records of *Boreogadus* and *Arctogadus* observed under sea ice dated back to the 1940s (Andriyashev 1957). Since that time, observations were reported in almost every decade, ranging from only one report per decade between 1950 and 1980, to up to nine reports between 2011 and 2019. No observations were reported between 1991 and 2000 (**Table 4.2**). The vast majority of reported observations were performed using effective, but non-quantitative sampling equipment, such as traps, hand nets, hooked lines and observations by SCUBA divers. Quantitative information on under-ice fishes is scarce and was based on line transect surveys by divers (Gradinger & Bluhm 2004), bottom trawls (Hop & Gjøsæter 2013). Reported *Boreogadus* abundances from under-ice trawls vary significantly, ranging between 0 ind. km^{-2} to 16,000 ind. km^{-2} (David et al. 2016, Flores et al. 2016, 2018). The few available reports on potentially sympagic *Arctogadus* were from the western Arctic Ocean (Walters 1961, Andriyashev 1957, Andriyashev et al. 1980, Tsinovsky 1980, Bouchard et al. 2016).

Table 4.1. Results of database research with search terms relevant for the sympagic habitat. The literature searches were made in May 2019. n.a. = not applicable

Database	Search terms	No of publications	No of original Articles	No of reviews	No of other publications	Period
Web of Science	TS=((“Arctic Ocean” AND “sea ice” AND “fish*”) OR (“*Boreogadus*” AND “sea ice”) OR (“*Arctogadus*” AND “sea ice”))	126	109	15	8	1992-2019
Scopus	TITLE-ABS-KEY((“Arctic Ocean” AND “sea ice” AND “fish*”) OR (“*Boreogadus*” AND “sea ice”) OR (“*Arctogadus*” AND “sea ice”))	157	127	13	17	1986-2019
Google Scholar	“Central Arctic Ocean” “sea ice” “*Boreogadus*” “*Arctogadus*”	73	n.a.	n.a.	73	1971-2019
Publications. europa.eu	“Arctic Ocean” “fish*” “sea ice”	180	n.a.	n.a.	180	1990-2019

Observations on sympagic *Boreogadus* are available from all sectors of the Arctic Ocean, but comparable observations were never made in two or more regions during one year. The majority of observations of sympagic *Boreogadus* were made during summertime. However, year-round sampling on drift stations indicates that sympagic *Boreogadus* are found throughout the Arctic Ocean during all seasons (Walters 1961, Andriyashev 1957, Melnikov & Chernova 2013, Bouchard et al. 2016). All studies reporting size data on sympagic *Boreogadus* indicated that the under-ice population consists mainly of first year and second year juveniles (e.g. Bradstreet & Cross 1982, Lønne & Gulliksen 1989, Melnikov & Chernova 2013, David et al. 2016). It has been proposed that these young sympagic *Boreogadus* were recruited from late-hatched cohorts on the shelves that were accidentally advected into the CAO. However, a study using acoustic telemetry of tagged young *Boreogadus* showed they perform long-distance seasonal migrations, indicating that they would be able to counter-act advection into unfavourable areas (Kessel et al. 2017). Another hypothesis suggested that the sea ice is used as a transport vector connecting different populations around the Arctic Ocean (David et al. 2016).

A large body of literature is available on the diet of *Boreogadus*, as well as its role as a prey item for Arctic seabirds and mammals. Only few reports on the trophic ecology of *Boreogadus*, however, are available from *Boreogadus* dwelling under Arctic sea ice. These studies show that sympagic *Boreogadus* feed predominantly on sympagic invertebrates, such as ice amphipods and copepods grazing ice algae (Lønne & Gulliksen 1989, Bouchard et al. 2016, Kohlbach et al. 2017). Studies on seabirds foraging in ice-covered waters indicate that sympagic *Boreogadus* constitute an important food source for the birds (Lønne & Gabrielsen 1992, Mehlum & Gabrielsen 1993). Linking the presence of *Boreogadus* in the diet of warm-blooded predators to sea ice habitats, however, is inherently associated with uncertainties, as long as the predator was not observed catching fish from the under-ice habitat.

Table 4.2. Observations of ice-associated fishes in the Arctic Ocean. * = summarized in Mecklenburg et al. (2014). Observation type is not specified as e.g. numbers here because the reported numbers have very different dimensions (e.g. observations per minutes, numbers of fish caught, abundance in individuals km^{-2}, etc.) and were obtained with very different methods (SCUBA diving, dynamite, landing net, under-ice trawl, etc.), which makes it impossible to compare them. The important point here is whether data were at all available in quantitative terms. This table shows that there is very little quantitative information available, but many reports indicate the "presence" of fish, which is very important. We believe it is much more valuable to know the quality and type of the data than some incomparable figures.

Species	Year	Region	Season	Source	Sampling method	Observation type
Boreogadus	1972-2011	Barents Sea	Various seasons	Hop & Gjøsæter (2013)	Time series analysis	Abundance, distribution and ecology
Boreogadus	1985-1986	Barents Sea, north of Svalbard	Summer	Lønne & Gabrielsen (1992)	Sea bird survey and sampling	Presence in diet of seabirds foraging in ice-covered waters
Boreogadus	1986-1987	Barents Sea, north of Svalbard	Summer	Lønne & Gulliksen (1989)	Divers and traps	Presence and diet
Boreogadus	2017	Barents Sea, north of Svalbard	Spring	Flores et al. (2018)	Under-ice trawl	Abundance and distribution
Arctogadus & *Boreogadus*	2004 and 2008	Beaufort Sea	Summer	Bouchard et al. (2016)	Under-ice net	Presence and diet
Boreogadus	1979	Canadian Arctic Archipelago	Summer	Bradstreet & Cross (1982)	Divers, traps and spears	Presence
Boreogadus	2012	Canadian Arctic Archipelago	Summer	Kessel et al. (2017)	Acoustic tagging	Presence and behaviour
Boreogadus	2012-2013	Canadian Arctic Archipelago	Summer	Kessel et al. (2016)	Acoustic tagging	Presence and behaviour
Arctogadus & *Boreogadus* *	1940s to 1980s	CAO	Various seasons	Andriyashev (1957) Andriyashev et al. (1980), Tsinovsky (1980), Tsinovsky (1981)	Hand nets and hooked lines from drift stations	Presence
Boreogadus	2002	CAO (Canada Basin)	Summer	Gradinger & Bluhm (2004)	Under-ice survey (divers)	Distribution and behaviour
Boreogadus	2009-2010	CAO (Canada Basin)	Winter	Melnikov & Chernova (2013)	Under-ice sampling (net)	Presence and behaviour
Boreogadus	2012	CAO (Eurasian Basin)	Summer-autumn	David et al. (2016)	Under-ice trawl	Abundance and distribution
Boreogadus	2012	CAO (Eurasian Basin)	Summer-autumn	Kohlbach et al. (2017)	Diet & biomarker analysis	Diet and carbon sources
Boreogadus	2012-2015	CAO (Eurasian Basin)	Spring, summer, autumn	Kühn et al. (2018)	Microplastic analysis	Microplastic ingestion
Arctogadus & *Boreogadus*	1959-1960	Chukchi Sea	Summer	Walters (1961)	Dynamite ice fishing	Presence
Boreogadus	1978-1979	Chukchi Sea	Year-round	Tsinovsky (1981)	Divers and hand nets	Presence
Boreogadus	2015	North of Svalbard	Spring	Flores et al. (2016)	Under-ice trawl	Abundance and distribution
Boreogadus	1982-1990	Svalbard region	Summer	Mehlum & Gabrielsen (1993)	Sea-bird survey and sampling	Presence in diet of seabirds foraging in ice-covered waters

Analysing genetic diversity and decomposing single species into genetic units, e.g. (sub-) populations, is important to understand biogeographical patterns and stock structure, and to improve predictions on the effects of climate change on the distribution range, abundance, competition with boreal species and role in the food web (Marcer et al. 2016, McNicholl et al. 2018). Despite the ecological significance of *Boreogadus* and *Arctogadus*, their large-scale population structure and connectivity patterns remain largely undescribed.

Ghigliotti et al. (2005) found chromosomal intraspecific polymorphisms in *Boreogadus* and *Arctogadus*, and two karyomorphs (2n = 36, 38) and three karyomorphs (2n = 28, 30, 32), respectively. These preliminary results point to a degree of genomic plasticity. Mitochondrial and nuclear DNA markers, such as DNA microsatellite markers (also called "Single Sequence Repeats") also provide valuable information on intraspecific variation. Sets of 19 and 16 microsatellite loci were used for the examination of the population genetics of *Boreogadus* and *Arctogadus*, respectively (Nelson et al. 2013). The number of alleles observed for each locus ranged from 3 to 33 in *Boreogadus* and 1–22 in *Arctogadus*. Observed heterozygosities ranged from 0.02 to 0.93 in *Boreogadus* and 0.17–1.0 in *Arctogadus*. Species-specific differences were observed at selected loci providing identification tools of these two morphologically similar Arctic gadids (Nelson et al. 2013).

In the northern Atlantic Ocean, little to no geographic structure of *Boreogadus* was found (Fevolden et al. 1999, Pálsson et al. 2009). In the Pacific Arctic Ocean, Wilson et al. (2017) described overall high levels of genetic diversity, but no spatial divergence within and between Beaufort, Bering, and Chukchi Sea *Boreogadus*. On the other hand, Madsen et al. (2016) described genetic differentiation between fjord and oceanic *Boreogadus* in the Greenland Sea. Hence, a high level of connectivity across the Arctic Ocean and differentiation between inshore and offshore populations point to spatially differentiated evolutionary dynamics of *Boreogadus*. Ongoing genomic studies with high resolution markers aim at differentiating between neutral and adaptive evolution (Volckaert, pers. comm.). In addition, biophysical modelling of larval dispersal, such as implemented in northern Atlantic species, is a promising tool to understand the distribution and population dynamics (Hufnagl et al. 2017, Barbut et al. 2019). No population genetic studies or genomic studies (Baalsrud et al. 2018) focussing on stock structure of *Arctogadus* have been published.

4.5. Critical gap analysis

Our review of the published observation of ice-associated fishes in the Arctic Ocean shows that records on the two sympagic species *Boreogadus* and *Arctogadus* are scattered in space and time (**Table 4.2**). The knowledge base on *Arctogadus* is particularly thin. This species appears to be mainly distributed in the Amerasian sectors of the Arctic Ocean and, so far, there is no evidence of sympagic *Arctogadus* in the Eurasian sectors. Only few studies sampling *Boreogadus* under Arctic sea ice also found *Arctogadus* (Walters 1961, Andriyashev 1957, Andriyashev et al. 1980, Tsinovsky 1980, Bouchard et al. 2016), indicating that this species may not be as much associated with sea ice as *Boreogadus*. This notion is supported by a more benthic diet compared to *Boreogadus* (Bouchard et al. 2016).

If we combine all observations from almost eight decades, we may conclude that young *Boreogadus* are found associated with sea ice throughout the Arctic Ocean (**Table 4.2**). Due to the poor spatial coverage in any given year, however, there is no solid evidence of a continuous distribution range. More importantly, the few available semi-quantitative abundance estimates using varying methods at different spatial scales impede pan-Arctic estimates of population sizes, distribution patterns and investigations of their inter-annual variability. In addition, since studies on sympagic *Boreogadus* were not combined with pelagic or benthic sampling, there is no information on which proportion of the standing stock in a given area is sympagic compared to pelagic and benthic distributions, and whether vertical migrations take place between the different depth layers. Only two studies investigated the distribution of under-ice *Boreogadus* in relation to sea ice habitat properties, and found that higher fish abundance was associated with thicker ice, higher ice coverage and lower surface salinity, or with higher densities of the ice-amphipod *Apherusa glacialis* (Gradinger & Bluhm 2004, David et al. 2016). To predict the effect of changing sea-ice habitats on the distribution of sympagic *Boreogadus*, however, detailed knowledge about the association of *Boreogadus* with sea-ice habitat properties and its geographic and seasonal variability would be crucial. Another important aspect for future predictions is whether adult or juvenile *Boreogadus* undertake horizontal migrations, potentially through deep waters, in order to return to spawning areas. The few available studies indicate that they may passively drift with sea ice across the CAO, but that they are also capable of migrations over distances of hundreds of kilometres (David et al. 2016, Kessel et al. 2017). To date, there is no solid evidence of long-range migrations across the Arctic Ocean, or of migrations of individual fish from one spawning stock to another. The effect of such trans-polar migrations on the gene flow between populations is presently not understood due to a lack of high-resolution sequencing studies of the fine-scale population structure around the Arctic Basin. To assess the viability of sympagic *Boreogadus* populations at present and under future scenarios, quantitative information about their diet composition and prey populations is also essential. A diet study in the Eurasian Basin found that sympagic *Boreogadus* source the bulk of their carbon demand from ice algal production, by feeding on sympagic amphipods and copepods dwelling at the ice-water interface (Kohlbach et al. 2017). An assessment of the food demand of the fish population and the standing stock biomass of their prey species indicated that, even in the low-productive CAO, prey stocks were sufficient to support the observed abundances of sympagic *Boreogadus* (David et al. 2015, 2016, Kohlbach et al. 2017). The few available diet studies on sympagic *Boreogadus*, however, are insufficient to conclude about the geographic, seasonal and inter-annual variability of their feeding and prey availability (**Table 4.2**).

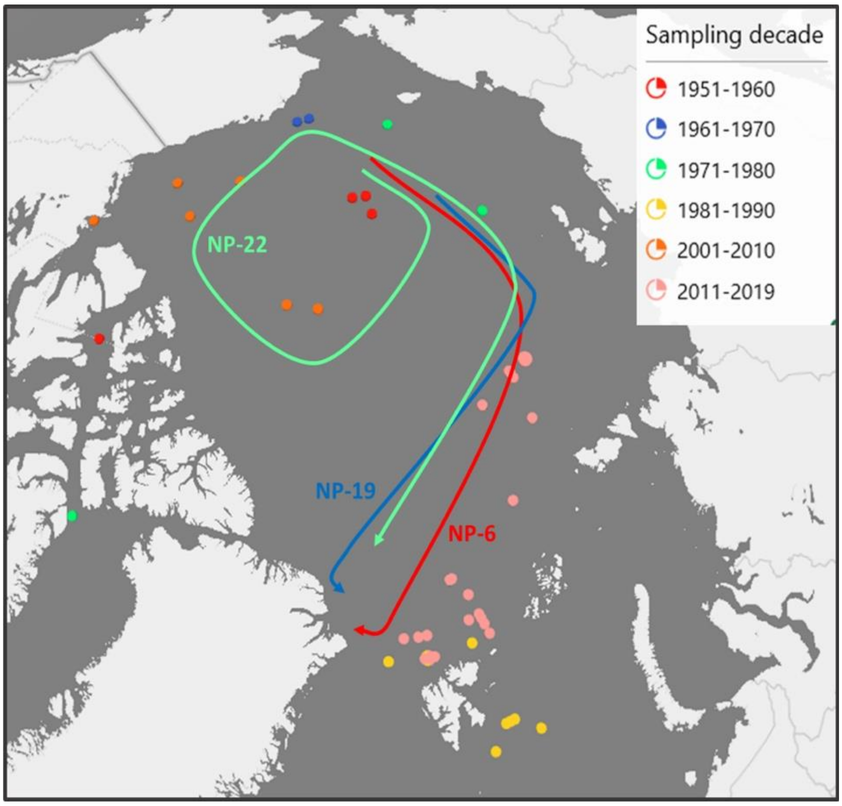


Figure 4.1 Spatial coverage of reported samples of *Boreogadus* or *Arctogadus* under sea ice as shown in **Table 4.2**. The sample locations are grouped by sampling decade. The arrows indicate the approximate drift trajectories of the 3 Russian drift stations from which *Boreogadus* were reported: NP-6 (1956-1958), NP-19 (1969-1970), and NP-22 (1973-1982).

Based on the scant quantitative information on sympagic *Boreogadus* available to date, their total population size in the CAO remains undetermined. We also have limited knowledge about the connection between sympagic and mesopelagic populations, vertical migrations, seasonal patterns of habitat use and feeding, and gene flow between populations. Besides *Boreogadus*, *Arctogadus* can also associate with sea ice during part of its life cycle. Knowledge in their occurrence in coastal waters is limited, and their potential distribution in the CAO is unknown. The present documentation of observations of sympagic fishes in the Arctic Ocean is likely biased towards western literature. More information may become available as historic publications from Russian/Soviet authors would become accessible through translation and digitalization. Stronger efforts to integrate knowledge of local and indigenous communities may further enhance the knowledge base on sympagic fishes.

Future research on Arctic sympagic fishes should aim for more comprehensive and standardised quantitative surveys of sympagic fishes in combination with environmental properties. A key focus should be on large-scale studies in order to estimate standing stock sizes, on vertical and horizontal migrations, and on the seasonal variability of fish distribution, their feeding and prey stocks. New technologies, such as autonomous hydroacoustic buoys with upward-looking echosounders, gliders and AUVs must be used to obtain a quantitative understanding of fish distribution under Arctic sea ice.

Table 4.3. Critical gap analysis for variables relevant for species, population dynamics and distribution of sympagic fish in the CAO. Estimate of severity of the knowledge gap: 0 = no knowledge, 1 = serious lack of knowledge, 2 = insufficient knowledge, 3 = sufficient knowledge available for the purpose indicated in column 2.

Variable	Why the variable is necessary to evaluate possibilities for potential future fisheries	Estimate of severity of the knowledge gap	What data needs to be collected to decrease the gap?
Sympagic distribution and abundance of *Boreogadus*	To estimate stock size and potential impact of potential fisheries on other target species on *Boreogadus*	1	Standardized abundances of *Boreogadus* throughout the Arctic Ocean from under-ice habitat
Sympagic distribution and abundance of *Arctogadus*	To estimate stock size and potential impact of potential fisheries on other target species on *Arctogadus*	0-1	Standardized abundances of *Arctogadus* throughout the Arctic Ocean from under-ice habitat
Horizontal and vertical migrations of *Boreogadus*	To understand migration patterns, refugee areas and critical bottlenecks for sustainable management	1	Tracking data, sea ice and ocean models, otolith tracers
Genetic population structure & gene flow	To identify populations and subpopulations for sustainable management	2	Next Generation Sequencing for high-resolution population genomics
Winter survival	To establish mortality indices for sustainable management	1	Winter condition, migration patterns and winter prey field
Food sources	To estimate carrying capacity for future ecosystem scenarios	2	Year-round diet and ontogenetic changes, sympagic prey stocks
Sympagic predators	To estimate impact of fish mortality on ecosystem performance	2	Predator censuses (sympagic seals and birds) and diet studies

Chapter 5. Food web and trophic interactions

Barbara Niehoff (AWI), Hauke Flores (AWI)

5.1. Chapter summary

Arctic gadoid fishes are planktivorous and thus depend on the availability of their prey, mainly copepods and amphipods. Especially the large, lipid rich *Calanus* species (Copepoda) rely on (the relatively large) diatoms, from both sea ice and water column. Ice algae are also the dominant prey for e.g. the herbivorous amphipod *Apherusa glacialis*. Carnivorous amphipods such as *Themisto libellula* feed on *Calanus*, also channelling algal production to higher trophic levels. In the CAO, the zooplankton biomass is low as compared to the marginal ice zone and shelf areas; high abundances are only associated with the inflow of Atlantic water. The vertical zooplankton distribution, and thus the prey field of Arctic fishes, changes from maximum abundances in the sea-surface layer in summer to maximum abundances in deeper waters in winter. Increasing inflow of warm Atlantic water into the Arctic, ocean acidification and receding sea-ice cover promote the dominance of small phytoplankton cells such as flagellates. Boreal zooplankton species migrate further north and environmental changes may alter the vertical zooplankton distribution. Such shifts in the pelagic community are expected to severely impact the population dynamics of Arctic fishes and, thus, ecosystem functioning and services.

5.2. Background

Arctic gadoid fishes are prey of many marine mammals and birds (Bluhm & Gradinger 2008). At the same time, they - as zooplanktivorous species - depend on the availability of their prey, mainly copepods and amphipods (Bradstreed & Cross 1982). While there are many studies on distribution, community composition and population dynamics of zooplankton in the Northern Hemisphere (e.g. 1010 publications listed by the Web of Science (WoS) for zooplankton and "North Atlantic"), much less is known on the zooplankton in the Central Arctic Ocean (CAO). The general consent is that the zooplankton biomass is quite low in the CAO (Mumm et al. 1998, Auel & Hagen 2002, Kosobokova & Hirche 2002). Recent studies by David et al. (2015) and Kohlbach et al. (2017) nevertheless indicate that the zooplankton prey stocks may be sufficient to support the observed abundances of sympagic *Boreogadus* (see **Chapter 4**). Our knowledge has, however, mostly been derived from summer studies; data on population dynamics and distribution patterns in the CAO in winter are scarce. This chapter summarizes the literature on zooplankton in the CAO, focusing on the two large crustacean orders, copepods and amphipods, which not only dominate the communities (copepods usually contribute at least 60% of the zooplankton biomass) but are also the main food sources for *Boreogadus* and *Arctogadus*.

5.3. Summary of literature searches

We searched for publications on zooplankton dynamics in the CAO in the public research databases Web of Science, Scopus, Google Scholar, and Publications.europa.eu, using a large variety of terms (e.g. "Arctic Ocean", "zooplankton", "food web", "fish", "diet" and "*Calanus*"; see **Table 5.1** for specific terms). The searches addressed all types of publications, except for Publications.europa.eu where legal documents were excluded. In general, the output of all databases was low (**Table 5.1**), with Google Scholar yielding the maximum of 51 publications and the broadest temporal coverage (1968-2019). Searches in the databases Web of Science and Scopus found 42 and 29 publications, respectively, and covered almost the same period (1978-2018/2019). In these two databases, the number of original articles clearly prevailed (**Table 5.1**). The European database Publications.europa.eu returned lowest number of publications (11) and covered only recent years (2001-2017). Here, the publications were dominated by reports directed at policy and resource management.

Table 5.1. Results of database research with search terms relevant for the food web and trophic interactions in the CAO. n.a. = not applicable.

Database	Search terms	No of publications	No of original Articles	No of reviews	No of other publications	Period
Web of Science	TS= ((“Central Arctic Ocean” AND “zooplankton”) OR (“Central Arctic Ocean” AND “*Calanus*”) OR (“Central Arctic Ocean” AND “food web”) OR (“Central Arctic Ocean” AND “food” AND “fish*”))	42	32	10	3	1978-2019
Scopus	TITLE-ABS-KEY ((“Central Arctic Ocean” AND “zooplankton”) OR (“Central Arctic Ocean” AND “*Calanus*") OR (“Central Arctic Ocean” AND “food web”) OR (“Central Arctic Ocean” AND “diet" AND “fish*”))	29	27	2	n.a.	1978-2018
Google Scholar	“Central Arctic Ocean” “zooplankton” “food web *” “fish*” “diet” “*Boreogadus*” “mesopelagic”	51	n.a.	n.a.	51	1968-2019
Publications. europa.eu	“Central Arctic Ocean” “zooplankton” “food web*” “fish*” “diet”	11	n.a.	n.a.	11	2001-2017

The original articles (**Table 5.2**) mainly provide data on abundance, biomass and distribution of the zooplankton communities captured mostly during summer. Moreover, some papers, although found by using “Arctic Ocean” as a search term, do not present data from the CAO but from adjacent areas such as Fram Strait (Kraft et al. 2013) and the Greenland Sea (Tremblay et al 2006). Unfortunately, the literature research did not provide key publications such as Kosobokova & Hirche (2009), Kosobokova & Hopcraft (2010) and Kosobokova et al. (2011), or the review paper by Bluhm et al. (2015), because they used “Arctic Central Basin” or “Canada Basin” instead of “Central Arctic Ocean”.

5.4. Summary of knowledge

The marine food web of Arctic shelf seas and its changes associated with decreasing ice cover have been summarized by CAFF (2017, **Figure 5.1**). For the CAO, no such illustrations exist because of severe gaps in our knowledge about the food-web components and their interactions. It is expected that the marine food web in the CAO has less components than the food webs in Arctic shelf seas (e.g. no Atlantic cod or capelin) and that it is less productive. In the CAO, the extreme seasonality in the light regime and the (permanent) sea-ice cover severely limits the primary production and, consequently, the biomass of zooplankton is low as compared to the marginal ice zone and the shelf areas of the Arctic (reviewed by Bluhm et al. 2015; **Figure 5.2**). For example, Auel & Hagen (2002) have shown that the biomass in summer in the CAO integrated over the upper 1,500 m of the water column was 2.0 (SD 0.3) g Dry Mass

(DM) m^{-2}. In the relatively shallow and not permanently ice-covered Barents Sea, biomasses integrated over the upper 200 m were between 5 and 22 g DM m^{-2} with highest values associated with the inflow of Atlantic water (Dalpadado et al. 2003). Similarly, Kosobokova & Hirche (2009) found low biomass (1.9 DM g m^{-2}) in the centres of the Arctic basins north of 86 ^{o}N while the biomass was elevated along the Eurasian continental margin in relation to the advection of Atlantic pelagic populations, and the highest biomasses (up to 23.9 DM g m^{-2}) were associated with the core of the Atlantic inflow. Thus, the zooplankton biomass, which could support fish stocks seems to be much lower in ice-covered areas as compared to the slopes and shelfs with open-water regions, and the carbon flux from primary production to higher trophic levels appears to be comparably low in the CAO.

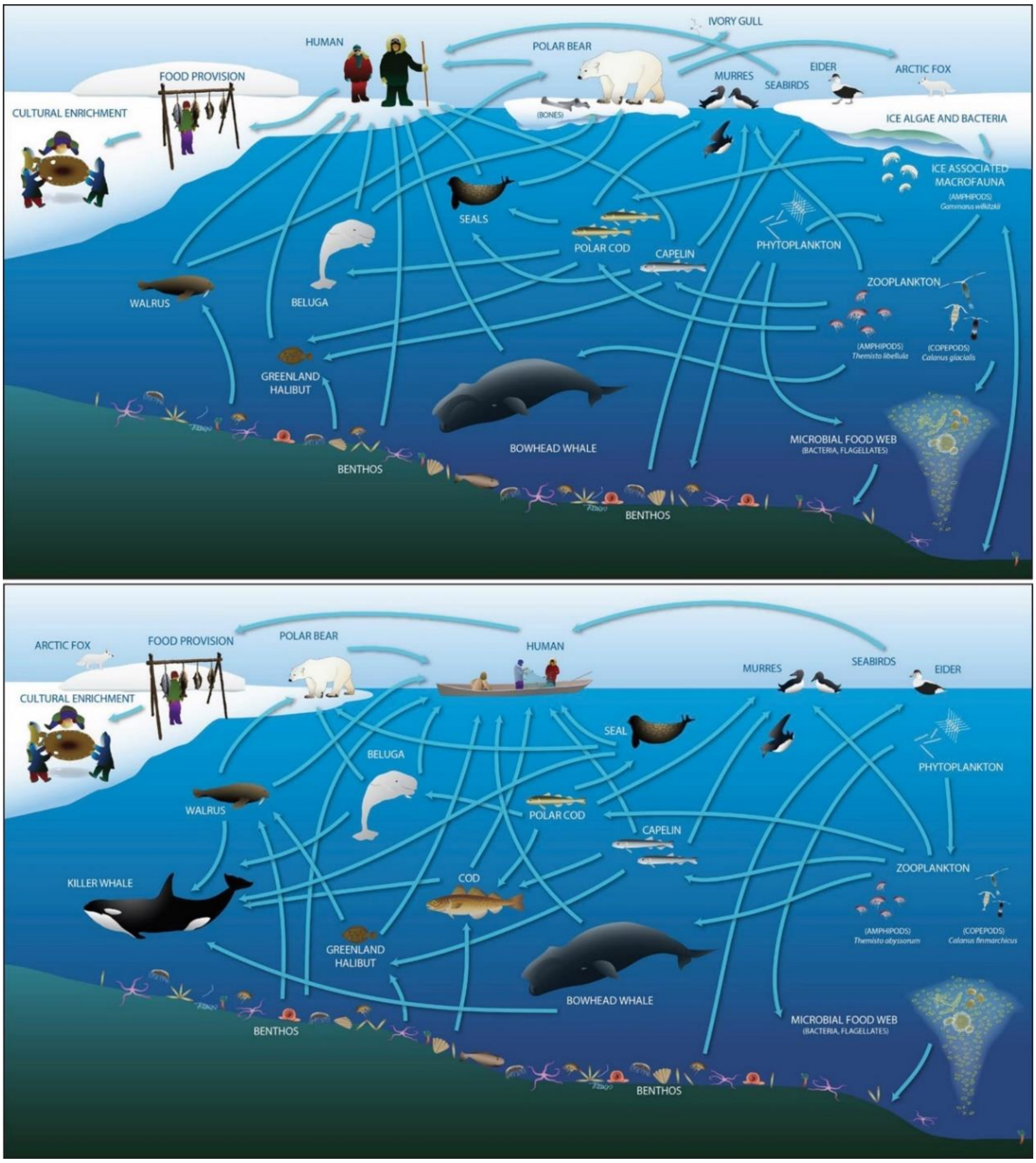


Figure 5.1. Concepts of energy flows at the ice edge in the Arctic shelf seas; the food-web structure in the CAO is yet unknown but is expected to be different (e.g. without Atlantic cod and capelin). Upper panel: Through the Arctic marine food web, energy and nutrition are transferred from primary producers to higher trophic levels including birds, fish, mammals, and humans. Lower panel: Changes expected or underway in the energy flow in the High Arctic marine environment. Figure from CAFF (2017).

Table 5.2. Relevant papers for the food web and trophic interactions in the CAO identified by the database research presented in **Table 5.1**.

Taxon	Year	Region	Season	Source	Sampling method	Observation type
Copepods	1970-1972	CAO	All seasons	Dawson (1978)	Vertical net	Population study
Mesozooplankton	1987-1991	CAO	Summer	Mumm et al. (1998)	Vertical net	Community study & distribution analysis
Mesozooplankton	1994	CAO	Summer	Thibault et al. (1999)	Vertical net	Community study & distribution analysis
Mesozooplankton	1991	CAO	Summer	Auel & Hagen (2002)	Vertical net	Community study
Mesozooplankton	1993-2000	Greenland Sea	All seasons	Møller et al. (2006)	Vertical net, pump	Community study
Zooplankton	1998	North Water Polynia	Spring-summer	Tremblay et al. (2006)	Various	Food web study
Amphipods	2001-2012	Fram Strait	All seasons	Kraft et al. (2013)	Sediment traps	Population study
Under-ice fauna	2012	CAO	Summer-autumn	David et al. (2015)	Under-ice trawl	Community study
Under-ice fauna	2012	CAO	Summer-autumn	Kohlbach et al. (2016)	Under-ice trawl	Food web study
Boreogadus	2012	CAO	Summer-autumn	Kohlbach et al. (2017)	Under-ice trawl	Diet study
Calanus hyperboreus	1934-2015	CAO	All seasons	Kvile et al. (2018)	Various	Lyfe cycle study

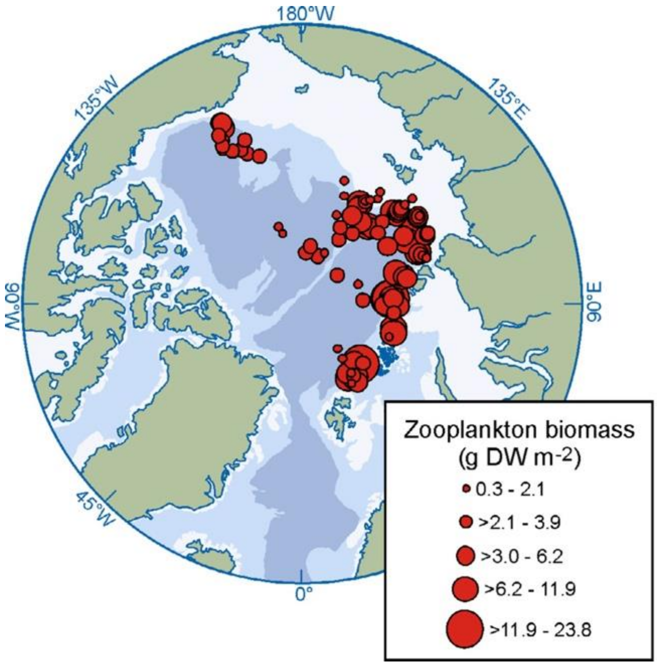


Figure 5.2. Zooplankton biomass (g dry weight m^{-2}) distribution in the Arctic Ocean. Note that there are only a few stations in the CAO while shelf and coastal areas are relatively well studied. Figure from Bluhm et al. (2015).

The mesozooplankton biomass distribution is often high at the surface and decreases with depth (Auel & Hagen 2002, Kosobokova & Hirche 2009). In summer in the CAO, the highest mesozooplankton values of up 26 mg DM m^{-3} were found in the upper 50 m (Auel & Hagen 2002), whereas the biomass did not exceed 2 mg DM m^{-3} in the layer between 200 and 500m, and was even lower below 500 m (Auel & Hagen 2002). All studies have used plankton nets deployed from research vessels and could therefore not consider that the ice provides a special habitat for not only fishes but also for zooplankton (Werner & Martinez Arbizu 1999, Hop et al. 2000, Werner & Gradinger 2002, Werner & Auel 2005, David et al. 2015, Kohlbach et al. 2016). The food regime for the Arctic fish may thus not only be evaluated by the total biomass per m^2 but also by its vertical and horizontal distribution, leading to food patches which can more easily be exploited by fish.

In terms of species inventory in the central Arctic basins, a total of 174 multi-cellular zooplankton species from eight phyla were registered, dominated by crustaceans, and primarily copepods (Kosobokova et al. 2011). Among these, copepods and amphipods constitute major food sources for Arctic planktivorous fish (Bradstreet & Cross 1982). Arctic copepods cover a wide size range, from eggs and nauplii of about 50 µm diameter to adult females and males of up to 2 cm lengths (Mauchline 1998). In most marine food webs, herbivorous calanoid copepods are an important link between primary production and higher trophic levels, and the herbivorous species may even control phytoplankton development in marine areas (Bathmann et al. 1990, Båmsted et al. 1991, Nejstgaard et al. 1995). While larger copepodites and adult copepods are mainly consumed by fishes, whales and larger invertebrates (e.g. Hardy 1924**,** Gaskin 1982, Lough & Mountain 1996), fish larvae often feed on eggs and nauplii (e.g. Fortier et al. 1995, Michaud et al. 1996). Thus, knowledge on the population dynamics of calanoid copepod is essential for the understanding and the quantification of fish recruitment (Runge 1988). However, the data on the timing of life cycle events such as spawning and ontogenetic migration in copepods, or the release of offspring from brood pouches of amphipods, have mostly been gathered in Arctic ice-free (shelf) areas and in fjords but not in the CAO.

In the CAO, three large, lipid rich *Calanus* species, *C. hyperboreus*, *C. glacialis* and *C. finmarchicus* dominate the mesozooplankton biomass (Auel & Hagen 2002). *C. hyperboreus* is dominating the community in the basins of the CAO (Dawson 1978, Kosobokova 2003). From studies in Arctic shelf sea areas and fjords (e.g. Hirche 1998, Madsen et al. 2001, Kosobokova 2003, Søreide et al. 2008), it is well known that all three species perform strong vertical migration. During the productive season, they reside in surface waters (0-50 m), where feeding on pelagic unicellular algae fuels reproduction (Niehoff et al. 2002, Olli et al. 2007). *C. glacialis,* however*,* is long known to feed also on ice algae, which develop prior to the phytoplankton in the water column (Runge & Ingram 1991). Thus, they are able to start feeding and reproducing early in the season (Niehoff et al. 2002). *C. hyperboreus* has another reproductive strategy, producing eggs while residing at depth during winter based on its lipid reserves (Hirche & Niehoff 1996, Niehoff 2007). The nauplii and the young copepodite stages then migrate to the surface where they exploit the phytoplankton bloom, developing to their overwintering stages. While at the surface, the *Calanus* species do not only reproduce (*C. glacialis* and *C. finmarchicus*) and grow but they also build up large lipid stores, which makes them an extremely rich food source (Falk-Petersen et al. 2007).

Data from the CAO on population dynamics and vertical distribution patterns of these three species are rare and have mostly been conducted during the summer season when the region is accessible by ice-breakers. Only very few studies (Dawson 1978, Ashjian et al. 2003, Kvile et al. 2018) cover several months to a year, confirming that also in the ice-covered Arctic ocean *Calanus* spp. perform ontogentic migration resulting in large shifts of biomass. This, in turn, considerably changes the prey field of Arctic fishes throughout the year. Whether or whether not also diel vertical migration (DVM) occurs, is still under debate. Some studies from the CAO did not find clear evidence for DVM (Kosobokova 1978, Groendahl & Hernroth 1984, Longhurst *et al.*, 1984) while more recent studies in the Svalbard region and in Barrow Strait indicate that (some) zooplankton species do perform diel vertical migration, even under ice cover (Fortier et al. 2001, Berge et al. 2009, 2012, 2015, Gjøsæter et al. 2017).

While research has often concentrated on the large *Calanus* species due to their crucial role in the lipid based Arctic food web, the smaller copepod genera *Metridia*, *Pseudocalanus*, *Microcalanus, Oithona,* and *Oncaea* have generally received less attention because of their lower contribution to the total biomass than *Calanus* spp., although they are numerically quite abundant in many areas (Mumm et al. 1998, Ashjian et al. 2003). Moreover, these species exhibit different feeding modes and thus, occupy different niches in the Arctic food web. *Metridia longa* and *Metridia lucens* are omnivorous and their abundance peaks between 200 and 500 m (Diel 1991, Ashjian et al. 2003), and these species remain active during winter. *Oithona* is mostly found in the upper 50 min, and produces egg-sacs likely year-round, while the small *Oncea* species are usually found deeper in the ocean where they feed on marine snow but also on other mesozooplankton. Our knowledge about the timing of reproduction, their vertical migration patterns during the season and their role in the food web of the CAO is very limited, but these species could serve as food sources for Arctic fishes during the phytoplankton scarce winter season when the large *Calanus* species inhabit their overwintering habitat at depth > 1,000 m.

Amphipods are usually larger than copepods and in contrast to copepods, which release their eggs into the water column or carry their eggs until hatching (Mauchline 1998), amphipods develop directly and carry their offspring in brood pouches, providing a food source of different quality. In the CAO, the two amphipod congeners, *Themisto libellula* and *Themisto abyssorum* co-occur sympatrically. They are carnivorous and prey on other mesozooplankton such as copepods, euphausiids, pteropods and chaetognaths (Hopkins 1985, Falk-Petersen et al. 1987). *Themisto abyssorum* is a subarctic-boreal species, and is transported into the Arctic Basin mainly by the West Spitsbergen Current. Accordingly, its abundance decreases from >200 individuals m^{-2} in the core of the Atlantic inflow to <40 individuals m^{-2} in the central Arctic basins (Mumm et al. 1998). *Themisto libellula* reaches maximum abundances in the polar surface water of the Arctic Ocean and is considered a true Arctic species (Koszteyn et al. 1995). Due to its presence near the surface, the latter species especially represents an important and stable resource for Arctic marine vertebrates such as *Boreogadus*, *Alle alle* (little auk) as well as for *Phoca hispida* (ringed seal) and *Pagophilus groenlandicus* (harp seal) in the Barents Sea (Węsławski et al. 1999, Wathne et al. 2000). Ice algae are the dominant prey for the herbivorous amphipod *Apherusa glacialis* which is one of the amphipod species that is closely related to sea ice during at least parts of the year (Kohlbach et al. 2016). Carnivorous ice amphipods channel the algal production to higher trophic levels indirectly, e.g. *Themisto* spp. feeding on *Calanus* spp.

5.5. Critical gap analysis

Most studies indicate that the primary production in the CAO is too low to sustain its zooplankton stocks and that the populations are transported into the CAO either with the inflow of Atlantic water or from the Arctic shelf seas (e.g. Auel & Hagen 2002). This could imply that food supply for fishes could be extremely limited during some times of the year, and even though the availability of the prey may not change significantly in terms of numbers, the zooplankton organisms may simply not be accessible due to vertical migration to the deeper ocean. However, as there are no data, we can yet not evaluate the biomass of overwintering zooplankton nor their distribution. The spatial coverage of the studies to date does also not allow for estimating transport and sustainability of zooplankton biomass in the CAO. Most data have been collected during the productive season which is short and shifted towards late summer/autumn as compared to late spring/summer in Fram Strait and the fjords around Svalbard (e.g. Daase et al. 2013, Nöthig et al. 2015), and our understanding of the population dynamics of the prey zooplankton organisms as gathered from other areas can only be partly applied to the

CAO. Studies on trophic interactions using modern methods (e.g. compound specific stable isotope analysis, Kohlbach et al. 2016) are almost completely lacking. The distribution patterns as described so far rely mostly on relatively coarse depth intervals (covering the whole water column with only a few samples) collected by multi-opening and closing plankton nets. Studies on the fine scale distribution of zooplankton, which can reveal food patches, are lacking from the CAO. Year-round studies are urgently needed to assess the zooplankton stock, their population dynamics, their trophic interactions and their distribution patterns and, thus, the prey field for Arctic fishes.

Increasing inflow of warm Atlantic water into the Arctic Ocean, acidification of sea-surface waters and receding sea-ice cover promote the dominance of small phytoplankton cells such as flagellates (Li et al. 2009), and boreal zooplankton species may expatriate into the CAO (Hirche & Kosobokova 2007). In addition, such transformations of the environment may lead to changes in the vertical distribution of zooplankton species, since species differ in their vertical distribution patterns. Subsequently, this has the potential to change the trophic interactions in the pelagic ecosystems of the CAO. For example, shifts in the pelagic zooplankton communities may have positive or negative consequences for the feeding regime and the population dynamics of the Arctic fishes and, thus, ecosystem functioning and services. For modelling the population dynamics and abundance of the fish stocks in the CAO and assessing the impact of climate change on zooplankton and fish, year-round studies and studies with a large spatial coverage on both prey and predators, are essential.

Table 5.3. Critical gap analysis for variables relevant for the food web and trophic interactions in the CAO. Estimate of severity of the knowledge gap: 0 = no knowledge, 1 = serious lack of knowledge, 2 = insufficient knowledge, 3 = sufficient knowledge available for the purpose indicated in column 2.

Variable	Why the variable is necessary to evaluate possibilities for potential future fisheries	Estimate of severity of the knowledge gap	What data needs to be collected to decrease the gap?
Stomach analyses of fish	Identification of prey ingested by fish	1	Stomach contents from fish in the CAO (year-round)
Stomach analyses of fish predators	Identification of prey ingested by birds and mammals	0	Stomach contents from birds and mammals in the CAO (year-round)
Zooplankton and sympagic fauna abundance	Estimation of prey biomass for Arctic fishes	1	Samples from the CAO year-round and covering large spatial scales
Zooplankton and sympagic fauna population dynamics	Identification of bottle necks of food availability	1	Gonad development and invertebrate size measurements from preserved samples from the CAO
Zooplankton and sympagic fauna migration behaviour	Estimation of prey availability	1	Vertical high-resolution sampling of zooplankton and sympagic fauna using multiple closing nets and optical methods
Hydrography and phytoplankton and ice-algal standing stocks	Identify driving environmental factors for zooplankton growth	2	Salinity, temperature and chlorophyll *a* measurements from the water column
Distribution and abundance of birds and mammals	Estimation of predator availability	1	Distribution and abundance of birds and mammals in the CAO

Chapter 6. Fish species/populations and climate change impacts: northward migrations

Hauke Flores (AWI), Fokje L. Schaafsma (WMR), Pauline Snoeijs-Leijonmalm (SU)

6.1. Chapter summary

We identified 130 fish species living in the in the Arctic Ocean. Only 17 of these species have been reported from the CAO, but up to 51 Arctic fish species could be able to live in the CAO based on their known habitat preferences in adjacent waters. In response to ocean warming and sea-ice decline, boreal and temperate fishes along the shelves expand their distribution ranges northward, bringing new fishes into the Arctic Ocean. Some of these, e.g. herring species and various cod fishes, are of commercial interest. This "borealisation" of the fish communities leads to increasing competition with resident Arctic species in the Arctic shelf seas, and a shift of the distribution ranges the resident Arctic species towards the CAO. The future viability of potential Arctic fish stocks will largely depend on the development of primary and secondary productivity in the Arctic marine ecosystems. Further sea-ice decline is expected to negatively affect the current dominance of *Boreogadus* in the Arctic Ocean, with potentially disruptive consequences for the Arctic ecosystems. Data on the distribution of fishes in the CAO constitutes the most eminent knowledge gap. Limited knowledge on Arctic fishes and ecosystems in combination with rapid environmental change requires a careful monitoring scheme covering multiple trophic levels.

6.2. Background

During the past decades, the Arctic Ocean has been experiencing a rapid decline in the duration and extent of its sea-ice cover and strong ocean warming, progressing from the margins towards the CAO. This transformation is predicted to continue in the coming decades, resulting in the change from a perennial sea-ice cover to seasonally ice-covered Arctic Ocean by the mid-21st century (Meier et al. 2014). These strong changes of the physical environment have been causing ecological changes, including changes in primary production, phenology and magnitude, in plankton community composition, and a decline of sympagic (ice-associated) megafauna (Wassmann 2011, Wassmann et al. 2011, Barber et al. 2015, van Leeuwe et al. 2018). Along the southern margins of the Arctic Ocean, boreal and temperate communities are expanding their distribution ranges northwards, ousting resident Arctic communities to the north (Ershova et al. 2015, Fossheim et al. 2015, Eriksen et al. 2017). This process has been termed "borealisation". For example, boreal and temperate species, e.g. *Ammodytes hexapterus* (Pacific sand lance) and *Gadus morhua* (Atlantic cod) have significantly expanded northwards in the Barents Sea, and the distribution ranges of polar fishes, e.g. the key forage fish *Boreogadus*, have shifted towards the CAO (Fossheim et al. 2015, Falardeau et al. 2017, Ingvaldsen et al. 2017). Dramatic increases in fishery yields in ice-free Arctic shelf seas have been projected (Cheung et al. 2010, Hollowed et al. 2013), primarily because boreal species replace Arctic species of lower commercial value. *Boreogadus* and other Arctic fishes have so far acted as major carbon transmitters in the food chains, sustaining top predators such as seals and polar bears (CAFF 2017), which are also important for artisanal hunting. The extent to which such ecosystem functions will be maintained in future Arctic food webs is unclear.

With depths of over 4,000 m, the CAO constitutes a polar deep-sea system with very low productivity due to its hitherto perennial sea-ice cover and low nutrient concentrations. Hence, the present CAO ecosystem is assumed to have no capacity to support harvestable fish stocks. In the future, borealisation will likely extend into the High Seas area of the Arctic Ocean including parts of the CAO. Reduced sea-ice coverage will increase light availability and, hence, primary production where sufficient nutrients are available. This could potentially lead to the establishment of new harvestable species in the Arctic High Seas. This possibility has raised concern that the establishment of an unregulated fishery on new resources may add additional pressure on Arctic ecosystems in the near future, with potentially detrimental effects on conservation goals and ecosystem services (FiSCAO 2017). Currently, there is no scientific basis for a sustainable management system due to the limited knowledge on key ecosystem parameters, distribution and potential stock sizes of fishes in the CAO and the bordering shallow waters of the Arctic High Seas.

Factors limiting the northward shift of polar fishes and the northward expansion of boreal species include primary and secondary productivity, sea-ice coverage, ocean dynamics and bottom topography. Since most harvestable species are shelf-associated, the shelf slopes constitute a natural boundary to their northward expansion. In large areas of the CAO, primary and secondary productivity are unlikely to increase much more in the 21st century due to low nutrient concentrations at present and in future projections (Vancoppenolle et al. 2013, Tremblay et al. 2015, Tedesco et al. 2019). Future projections of productivity, sea-ice coverage, and ocean dynamics are currently associated with large uncertainties, complicating predictions about the future viability of fish stocks in the CAO (van Leeuwe et al. 2018, Tedesco et al. 2019).

These uncertainties are currently challenging the development of marine governance and resource management regimes in the Arctic High Seas (e.g. Zou & Huntington 2018). This chapter reviews the available literature identifying boreal fish species that could potentially expand into the CAO. Furthermore, we assess the potential of the future CAO to support polar and invading boreal fish stocks. Following a scrutinized procedure to review the available literature using various databases, we perform a gap analysis to highlight crucial knowledge gaps currently hindering a sound assessment of the future potential of the Arctic High Seas to support potentially harvestable fish stocks, and to derive future research priorities.

6.3. Summary of literature searches

We conducted searches in the public research databases Web of Science, Scopus, Google Scholar, and Publications.europa.eu. The database queries yielded surprisingly different numbers of publications in the two scientific literature databases Web of Science (110 publications) and Scopus (356 publications) (**Table 6.1**). The vast majority of publications in these two databases were original research articles. However, only ca. 130 (less than 40 %) of the returned publications were deemed useful for the purpose of this chapter. Google Scholar yielded about the same number of hits (108) as the Web of Science (110), and there was a large overlap in the results between these two portals. Publications.europe.eu yielded the lowest number of hits (85) (**Table 6.1**). The documents returned by this portal were mainly reports directed at marine governance and resource management.

6.4. Summary of knowledge

In May 2019, the ICES/PICES/PAME Working Group (WGICA) listed 91 Arctic and Arctic-boreal fish species, plus 10 species with a mainly boreal distribution, reported from the "wider CAO area", i.e. including the adjacent shelves surrounding the basins (work in progress; Hein Rune Skjoldal, Co-Chair of WGICA, personal communication). "Arctic" in a biogeographical sense means species able to live in Arctic water at sub-zero temperatures, which may require special physiological adaptations (e.g. anti-freeze agents in body fluids) for species that come in contact with sea ice. Of the 101 fishes listed by WGICA, 51 species were found present (37 species) or likely to occur (14 species) in the CAO and the surrounding slopes. Eelpouts, which are to a large extent slope species, are the dominant fish family with 20 species in this area (14 recorded, 6 likely to occur). Sculpins is the second-largest group with 7 species in the CAO (3 recorded, 4 likely to occur). Sculpins are predominantly shelf species, and their occurrence in the CAO is generally on the upper slope. The third-largest group is snailfishes with 6 species (5 recorded, 1 likely to occur). Within the CAO LME (excluding the slopes), the corresponding numbers were 14 species recorded and 21 species likely to occur (Skjoldal et al. in prep.). In the WGICA list, the number of confirmed fish species recorded in the CAO (14) is slightly higher than those reported in a previous inventory by FiSCAO (2017), which reported 12 confirmed species for the CAO.

Table 6.1. Results of database research with search terms relevant for fish species/populations and climate change impacts, including northward migrations in the CAO. n.a. = not applicable

Database	Search terms	No of publications	No of original Articles	No of reviews	No of other publications	Period
Web of Science	TS=("Arctic Ocean" AND "fish*" AND ("chang*" OR "borealisation" OR "expans*"))	110	91	17	7	1993-2019
Scopus	TITLE-ABS-KEY ("Arctic Ocean" AND "fish*" AND ("chang*" OR "borealisation" OR "expans*"))	356	301	23	25	1987-2019
Google Scholar	"fish*" "chang*" "borealisation" "expans*" "Arctic Ocean"	108	n.a.	n.a.	108	2006-2019
Publications.europa.eu	"fish*" "borealisation" "Arctic Ocean"	85	n.a.	n.a.	85	1991-2018

We extended the preliminary WGICA list and account for a total of 130 species that have been observed in the Central Arctic Ocean and adjacent waters (**Appendix 1**). Of these 130 species, 93 are associated with the shelf or upper slope (0-1,000 m). Among these shelf-associated species, 31 are commercially relevant according to www.fishbase.org (**Appendix 1**). This portal reports the "human use" value of fishes based on FAO statistics and expert assessments. *Clupea harengus* (Atlantic herring), *Clupea pallasii* (Pacific herring), *Coregonus muksun* (muksun), *Eleginus gracilis* (saffron cod), *Gadus* (*Theragra*) *chalcogrammus*, *Gadus macrocephalus* (Pacific cod), *Gadus morhua* (Atlantic cod), *Hippoglossoides platessoides* (American plaice), *Limanda aspera* (yellowfin sole), *Mallotus villosus* (capelin), *Melanogrammus aeglefinus* (haddock), *Oncorhynchus gorbuscha*, *Oncorhynchus keta*, *Pollachius virens* (saithe), *Reinhardtius hippoglossoides* (Greenland halibut), *Scomber scombrus* (Atlantic mackerel) and *Sebastes norvegicus* (golden redfish) are considered fish of high commercial value (www.fishbase.org). Only 37 fishes are associated with deeper waters on slopes and in the central basins (**Appendix 1**). Given that reproduction habitats are present and if sufficient food is available, these species could potentially expand their distribution ranges northward into the CAO. Twelve of these deeper-dwelling species are commercially relevant. However, only three of them are considered of high commercial interest (www.fishbase.org): *Hypoglossoides platessoides* (American plaice), *Reinhardtius hypoglossoides* (Greenland halibut) and *Sebastes mentella* (beaked redfish).

Applying an approach based on the analysis of species autecology, projected environmental change and expert judgement, Hollowed et al. (2013) identified 13 temperate or boreal taxa of finfish with a potential to expand their distribution into the

Arctic Ocean (**Appendix 1**, in red). Hollowed et al. (2013) noted that certain species, such as Atlantic cod, may be subject to range expansion due to their habitat association, but that prevailing Arctic conditions will continue to impede the closure of their life cycle, e.g. by inhibiting spawning migrations by seasonal sea-ice. This is certainly also true for the Atlantic mackerel (a boreal, Atlantic and Meditterranean species) which in spite of its wide bathymetric distribution window is not expected to establish populations beyond its present distribution.

Fourteen out of the 130 fish species have a primarily Arctic distribution (**Table 6.2**). Continuing borealisation in combination with ocean warming and sea-ice decline will expose these species to increased competition for resources, new predators, thermal stress and habitat loss. The result is a northward shift of their distribution ranges, as observed by Fossheim et al. (2015). In the future, borealisation can be particularly critical for the Arctic species associated with shelf habitats, e.g. *Arctogadus* (**Appendix 1**). The distribution range of *Boreogadus* extends across the CAO due to the ubiquitous presence of juveniles in the under-ice habitat (Melnikov & Chernova 2013, David et al. 2016). Spawning, however, takes place on the shelves, exposing this species to the same threats as *Arctogadus*. The early life stages of *Boreogadus* are particularly sensitive to temperature rise. Model simulations based on physiological experiments have shown that embryonic tolerance ranges linked to climate simulations reveal that increasing CO_2 emissions [Representative Concentration Pathway (RCP) 8.5] will deteriorate the suitability of present spawning habitat for both Atlantic cod (*Gadus morhua*) and Polar cod (*Boreogadus saida*) by 2100 (Dahlke et al. 2018). Moderate warming (RCP4.5) may avert dangerous climate impacts on Atlantic cod but still leaves few spawning areas for the more vulnerable Polar cod, which also loses the benefits of an ice-covered ocean. Emissions following RCP2.6, however, support largely unchanged habitat suitability for both species, suggesting that risks are minimized if warming is held "below 2°C, if not 1.5°C," as pledged by the Paris Agreement (Dahlke et al. 2018).

Table 6.2. Summary of the distribution and commercial value of the 130 fish species that have been observed in the Arctic Ocean (**Appendix 1**). The number of "commercial" species refers to the sum of species with high commercial and commercial value according to www.fishbase.org.

Distribution	Number of fish species (distribution)	Number of fish species (commercial value)
Arctic	14	3
Boreal-Arctic	18	5
Temperate-Arctic	7	2
Atlantic-Arctic	30	4
Pacific-Arctic	15	6
Boreal	2	0
Temperate-Boreal	4	2
Atlantic-Boreal	18	7
Pacific-Boreal	12	6
Wider distribution	10	4
	130	**39**

Besides being able to accomplish their entire life cycle, fishes expanding or shifting their distribution range northward are required to find sufficient food resources in order to sustain viable populations. On the shelves, benthic secondary production will increase in some regions due to increased pelagic productivity, but it may decline in other regions due to reduced bentho-sympagic coupling and the lack of mass downfalls of ice-algae due to sea-ice decline (Kedra et al. 2015, Grebmeier et al. 2018). The past polar conditions with extensive sea-ice coverage have been favouring large zooplankton and sympagic fauna specialized in exploiting ice-algal blooms, and equipped with large lipid reserves to survive and reproduce in spite of long periods of food scarcity (e.g. Søreide et al. 2010). Immigration of smaller boreal zooplankton species on the shelves due to borealisation is expected to replace the large, lipid-rich zooplankton with more numerous but smaller, lipid-poor zooplankton (Weydmann et al. 2014, 2018). Where sufficient nutrients are available, however, the biomass of herbivorous consumers will increase due to increasing primary production (Ershova et al. 2015, Eriksen et al. 2017). Hence, the total fish stock size increase on the shelves and slopes with further climate warming, but with a different community composition (Eriksen et al. 2017, Haug et al. 2017).

In the CAO, predictions of the future primary productivity are associated with great uncertainties, but bloom periods of ice algae and phytoplankton will remain short since nutrient concentrations are predicted to remain low (van Leeuwe et al. 2018, Tedesco et al. 2019). Changes in the extent and phenology of sea ice will disrupt the life-cycles of sympagic grazers, especially those not adapted to survive in the water column (Kiko et al. 2017). Many abundant grazers depend specifically on ice algae as a carbon source (Kohlbach et al. 2016). Emerging mismatches of the timing of ice algal and phytoplankton blooms with the reproductive cycles of zooplankton could reduce reproductive success of key prey species for planktivorous fishes (Søreide et al. 2010).

6.5. Critical gap analysis

With no more than 17 confirmed species occurring in the CAO out of 37 species potentially living in the CAO below 1,000 m water depth (**Appendix 1**), the lack of data on the fishes in the CAO is the most eminent knowledge gap. There is no reliable information about the distribution ranges, migration patterns and population sizes of any fish species living in the CAO (see **Chapter 4**). In particular, the biomass of lanternfishes (Myctophidae) and other mesopelagic fishes that dominate the global fish biomass (Irigoien et al. 2014) is practically unknown. Without scientifically sound and quantitative knowledge about the species composition and population sizes of fishes in the CAO, the very foundation of any science-based management of biological resources in the CAO is lacking. Filling this knowledge gap, at least regarding the ecologically and economically most important species [e.g. *Boreogadus*, *Sebastes norvegicus* (golden redfish), *Reinhardtius hippoglossoides* (Greenland halibut)] is urgently needed to establish a baseline against which future changes can be assessed.

To assess the future potential of the CAO to support northward-shifting Arctic fishes and immigrating boreal species, reliable projections of primary and secondary productivity in the CAO and adjacent waters are essential. Currently, estimates of the future primary production in the CAO are associated with large uncertainties (Tremblay et al. 2015, Tedesco et al. 2019). Furthermore, the effect of changing sea-ice habitats on the composition and productivity of secondary producer communities is difficult to predict. The demise of sympagic fauna will negatively affect the capacity of the sea-ice system to make carbon available to the pelagic food web during wintertime and other periods of food scarcity. Declining taxonomic diversity in high-Arctic ecosystems (Melnikov 2018) could cause a decline of functional diversity, reducing resilience to environmental stress. Several studies suggest that changes in the physical properties and the phenology of the Arctic sea-ice cover will have negative effects on key prey species of Arctic fishes (Søreide et al. 2010, Leu et al. 2011, Kohlbach et al. 2016, 2017), but the magnitude and spatio-temporal variability of these effects cannot be quantified at the present state of knowledge. It is also unclear to which extent a decline of ice-associated secondary producers can be compensated by immigrating boreal and Atlantic zooplankton.

In the shallow parts of the Arctic High Seas, on the shelves of the Chukchi Borderland and the East Siberian Sea, borealisation may promote the productivity of commercially relevant fish stocks, such as *Sebastes mentella* (beaked redfish) and *Gadus macrocephalus* (Pacific cod). There is, however, only a limited understanding about the future carrying capacity of these ecosystems, as the prey stocks also undergo major transformations in terms of species composition, size distribution and secondary productivity (Wassmann 2011, Kedra et al. 2015). To assess the future distribution and potential stock sizes, more knowledge is needed about the habitat requirements of expanding and immigrating fishes regarding the viability of all life stages, and potential migration routes between foraging habitats and spawning habitats (Hollowed et al. 2013). Understanding the ability of Arctic habitats to support resident Arctic fishes and newcomers shifting their distribution ranges in the context of life-history traits will be the key to future projections of fish distribution in the Arctic Ocean.

The rapid borealisation of Arctic fish communities (Hollowed et al. 2013, Fossheim et al. 2015) could favour the development of new harvestable resources in the eastern parts of the Arctic High Seas situated on the shelf (e.g. the Chukchi Plateau). However, the future viability of such fish stocks will depend on the development of ecosystem productivity and the ability of newcomers to complete their life cycles in their new habitats. The ousting of resident Arctic fishes from the shelves brings the risk of local- to regional scale extinctions, with potential ramifications on ecosystem functions.

This review highlights once more the urgent necessity to map the presence and distributions of fish communities in the CAO. The CAO covers the largest part of the Arctic High Seas, and hence closing this knowledge gap is an essential prerequisite for the development of any sustainable management regime for biological resources in this region. In the CAO, range expansions are limited to deep-water species, such as lanternfishes and redfish (*Sebastes* spp.). The capacity of the CAO ecosystem to support harvestable stock sizes of, for example, redfish in the future is questionable. In addition, further sea-ice decline will negatively affect the viability of the present-day dominant *Boreogadus* in the Arctic High Seas, with potentially disruptive consequences for ecosystem functioning.

Besides a broader foundation of data on the distribution, physiological plasticity and life-cycle biology of fishes in the Arctic Ocean, improved models must incorporate this knowledge to develop more accurate predictions of future changes in fish distribution. The presently limited knowledge-base on Arctic fishes and ecosystems in combination with rapid environmental change warrant a careful monitoring scheme covering multiple trophic levels. Only after such comprehensive research, may the establishment of an ecosystem-based management regime be successful.

Table 6.3. Critical gap analysis for variables relevant for fish species/populations and climate change impacts, including northward migrations in the CAO. Estimate of severity of the knowledge gap: 0 = no knowledge, 1 = serious lack of knowledge, 2 = insufficient knowledge, 3 = sufficient knowledge available for the purpose indicated in column 2.

Variable	Why the variable is necessary to evaluate possibilities for potential future fisheries	Estimate of severity of the knowledge gap	What data needs to be collected to decrease the gap?
Presence, standing stock and population structure of fishes in deep basins of the CAO	Standing stock biomass and population structure are the basis of any science-based resource management and are necessary to understand potential niches becoming available to migrant species	0-1	Fish abundance and distribution in benthic, pelagic and cryo-pelagic habitats
Primary and secondary productivity	To estimate the present and future carrying capacity of the ecosystem as a prerequisite for sustainable management	1	Seasonal and spatial variation in primary production of ice algae and phytoplankton, abundance and physiological state of zooplankton and sympagic fauna
Distribution, migration and life cycles of fishes in the CAO	Life-history data are essential to determine recruitment, mortality and population connectivity in management models	0-1	Seasonal variability in fish distribution and abundance, tagging, otolith studies
Northward expansion of species distributions	Estimate competition effects and range shifts	2	Long-term monitoring of fish populations in both the CAO and the shelf seas

Chapter 7. Data needs for potential fisheries assessment and fish stock modelling

Joakim Hjelm (SLU), Jonas Hentati Sundberg (SLU)

7.1. Chapter summary

There is a total lack of basic data on the fish stocks in the High Seas of the CAO and this must be tackled by acoustic mapping and scientific surveys of the pelagic food web for a period of at least three years, followed by a monitoring program. The amount of new data from the CAO should be sufficient and from a large enough area to allow fisheries assessment modelling and scenario-building to understand the dynamics of the fish stocks in a changing environment. These field and modelling studies provide a basis for management recommendations and the development of a future monitoring program, e.g. by selecting indicator species, developing bio-indicators and pointing out areas of special interest. This could allow the potential development of sustainable, ecosystem-based fishing levels for CAO fish resources in a data-limited context by (1) modelling of indirect effects of fishing on lower trophic levels via trophic cascades using size-spectra, stage-specific or other trait-based modelling approaches parameterized with the data from the Agreement's Mapping Program, and (2) modelling connectivity between the North-East Atlantic and Arctic regions through the possible expansion of habitats of species in North-East Atlantic towards Arctic shelves and the CAO due to climate change.

7.2. Background

There is a total lack of basic data for the fish stocks in the High Seas of the Central Arctic Ocean (CAO). This knowledge gap can only be addressed by acoustic mapping and scientific surveys of the pelagic food web. Sufficient new data from the CAO and from a large enough area are needed to allow fisheries assessment modelling and scenario-building to understand the dynamics of the fish stocks in a changing environment. These field and modelling studies provide a basis for management recommendations and the development of a future monitoring program, e.g. by selecting indicator species, developing bio-indicators and pointing out areas of special interest. This could allow the potential development of sustainable, ecosystem-based fishing levels for CAO fish resources in a data-limited context. Here, we first describe the more traditional ways to do stock assessment and their data needs. Thereafter we discuss possible ways to use indirect ecological effects to potentially assess sustainable fishing levels.

7.3. Summary of literature searches

We conducted searches in the public research databases Web of Science, Scopus, Google Scholar, and Publications.europa.eu. The database queries yielded surprisingly different numbers of publications in the two scientific literature databases Web of Science (0 publications) and Scopus (84 publications) (**Table 7.1**). Most publications in Scopus were original research articles. Google Scholar (70) yielded about the same number of hits as Scopus (84). Publications.europe.eu yielded a lower number of hits (50) (**Table 7.1**). The documents returned by this portal were mainly reports directed at marine governance and resource management.

7.4. Summary of knowledge

Stock assessment is a modelling tool that provides key information in order to conserve and manage commercially exploited fish stocks (Sparre & Venema 1998). Stock assessments are traditionally based on models of fish populations that require three primary categories of information: catch, indices of biomass and/or abundance and biological parameters (Sparre & Venema 1998, Carruthers et al. 2014).

Table 7.1. Results of database research with search terms relevant for potential fisheries assessment and fish stock modelling in the CAO. n.a. = not applicable

Database	Search terms	No of publica -tions	No of original Articles	No of reviews	No of other publica-tions	Period
Web of Science	TS=((“Arctic Ocean” AND “stock assessment”) OR (“Arctic Ocean” AND “stock modelling”) OR (“Arctic Ocean” AND “fisheries assessment”))	0	0	0	0	1945-2019
Scopus	TITLE-ABS-KEY ((“Arctic Ocean” AND "stock assessment”) OR (“Arctic Ocean” AND “stock modelling”) OR (“Arctic Ocean” AND “fisheries assessment”))	84	80	4	0	2010-2019
Google Scholar	“Central Arctic Ocean” “stock assessment”	70	n.a.	n.a.	70	1992-2019
Publications. europa.eu	“Arctic Ocean” “stock assessment”	50	n.a.	n.a.	50	1995-2019

Catch data are usually collected through fisheries monitoring programs and mainly consist of information on the landings and discards of a determined species. These data are needed to have an indication of the amount of fish that has been removed from the system by the fishery in a given year. Indices of abundance and biomass ideally come from a statistically-designed, fishery-independent scientific survey of fish species throughout their stock’s distribution range. Such surveys collect data using standardized gears and sampling methods in order to provide a relative index of biomass or abundance over time. Abundance data do not come only from surveys using fishing gears but also from eggs, larvae, hydroacoustics and video surveys.

Biological data can be collected from fishery monitoring programs and fishery-independent surveys and can include information on size and age distribution, maturity, but also on natural mortality, growth, migration rates and species’ diet among the others. While simple assessment methods can work with only catch or abundance data, in order to move to more complex and reliable models, the collection of biological data is of paramount importance. According to Christiansen et al. (2014), almost no fisheries are present in the Arctic Ocean today that target “Arctic species” *sensu stricto* (only 3 out of 59 targeted species). Only in the case of *Boreogadus* some limited catch data are available for the Barents Sea. This implies that assessment methods that are based on past-catch information cannot be applied to most fish classified as Arctic species (see Appendix 1). As a consequence, in order to be able to assess the status of the CAO stocks of Arctic species at sea, only abundance and biological data (no catch data) can be used.

Trend- and survey-based modelling is one of such methods and consists in looking at the trends in the index of abundance and other stock size indicators to provide reliable indications of trends in stock metrics, such as total mortality, recruitment, and biomass. The drawback of those methodologies is that they are generally able to provide only relative trends in stock size and not absolute values of the size of the assessed population (ICES 2012). Some of these models have been, or are still, used to assess the status of stocks inhabiting the Arctic area, e.g. *Sebastes mentella* (beaked redfish) in Icelandic waters (Tallman et al. 2016). The survey-based assessment program SURBA (ICES 2003, 2004) is an assessment model that allows the estimation of levels of total mortality and cohort abundances based only on survey data. This method has been used in the past to get information about the stock status of fish stocks managed by ICES under the Arctic Fisheries Working Group (AFWG) and is still used to further analyse survey trends for the cod stock in the Barents Sea and Norwegian Sea (ICES 2018).

Another method that will be possible to use in the Arctic could also be the "Daily Egg Production Method", which allows the evaluation of the Spawning Stock Biomass from the quantity of eggs present in the sea (Stratoudakis et al. 2006). This method is particularly applicable for small pelagic species and has been used to assess the status of numerous stocks around the world (Stratoudakis et al. 2006 and references therein).

Production models are another category of assessment models based on only abundance and biological data. The S6 model, based on only length, can be theoretically applied when catch data are absent. However, these models need a catch function, which includes a possible fishery in the near future. Production models usually pool together recruitment, mortality and growth into a single production function and estimate the status of the stock in relation to its carrying capacity and important reference points such as Maximum Sustainable Yield (MSY). However, those methods require long time series of catches or landings and thus are less suited for the Arctic where fisheries have been historically scarce.

Optical technologies have been developed to survey marine species worldwide using non-destructive methodologies (Letessier et al. 2013, Jamieson 2016). Baited remote underwater video (BRUV) surveys can provide biomass estimations and are considered cost-effective, simple and accessible to many users (Watson & Huntington 2016). BRUVs results have been compared with results from traditional fishing gear methods showing high accordance on relative abundance estimates (Brooks et al. 2011, Santana-Garcon et al. 2014). This survey method has been used already in the Eastern Canadian Arctic to estimate abundance of Greenland shark, filling a major knowledge gap previously preventing the assessment and management of this species in this area (Devine et al. 2018).

Hydroacoustic surveys are also a powerful tool that can be used to obtain direct information on the abundance of a determined species at sea. Each species has a distinct acoustic signature that can be recorded by an echosounder. By integrating the strength of the acoustic signal of a determined species over the survey area, estimations of the total abundance can be obtained. This method is particularly valuable in extreme environments, such as the Arctic or the Antarctic, where fishing operations at sea are quite challenging. It allows the collection of a large amount of data with a minimum impact on the environment. However, it is important to note that not all species produce acoustic signals, so that this method might be applicable to only some of the Arctic species. This method is considered more reliable for pelagic fish species, while the applicability of hydroacoustic methods is less suited for demersal species. Some acoustic data coming from Arctic geological surveys of 2014 and 2016 have shown that acoustics is probably the most promising method to locate fish in the water column under the ice. However, further studies are needed to develop this research area (ICES 2017). The use of hydroacoustics to determine fish biomass could also be developed by integrating monitoring with the fishery industry, e.g. the assessment of Peruvian anchoveta where the industry delivers calibrated hydroacoustic data to be used in assessments.

As an alternative to these more traditional assessment methods, there exists more ecological-related possibilities to determine changes in stock productivity. These alternative ways could allow the potential development of sustainable, ecosystem-based fishing levels for CAO fish resources, but in a data-limited context by (1) modelling of indirect effects of fishing on lower trophic levels via trophic cascades using size-spectra, stage-specific or other trait-based modelling approaches parameterized with the data from the Agreement's Mapping Program, and (2) modelling connectivity between the North-East Atlantic and Arctic regions through the possible expansion of habitats of species in North-East Atlantic towards Arctic shelves and the CAO due to climate change.

7.5. Critical gap analysis

The lack of basic data for the fish stocks in the High Seas of the CAO is the major gap that needs to be filled in order to produce any kind of assessment on the fish stocks inhabiting this area.

Table 7.2. Critical gap analysis for variables relevant for fisheries assessment and fish stock modelling in the CAO. Estimate of severity of the knowledge gap: 0 = no knowledge, 1 = serious lack of knowledge, 2 = insufficient knowledge, 3 = sufficient knowledge available for the purpose indicated in column 2.

Variable	Why the variable is necessary to evaluate possibilities for potential future fisheries	Estimate of severity of the knowledge gap	What data needs to be collected to decrease the gap?
Biological data on fish in the CAO	Modelling and assessment of fish stocks	1 (limited data on sympagic fish exist)	Scientific surveys in all areas of the CAO, including fish population structure (length, weight, age) and food-web interactions
Abundance of pelagic fish in the CAO	Modelling and assessment of fish stocks	0	Scientific surveys in all areas of the CAO, including number and spatial and seasonal distribution of fish
Abundance of benthic fish in the CAO	Modelling and assessment of fish stocks	0	Scientific surveys in all areas of the CAO, including number and spatial and seasonal distribution of fish

Chapter 8. Data needs for governance and socio-economic development of potential fisheries

Susa Niiranen (SU), Anne-Sophie Crépin (KVA), Henrik Österblom (SU)

8.1. Chapter summary

Assessing the sustainability of possible CAO fisheries management requires a holistic understanding of the social-ecological system (SES) of the region, including not only estimates of future fish stocks, but also understanding of the supply and demand conditions for fish, the different economic sectors and actors to be present, as well as the governance structures and mechanisms already in place. To ensure the resilience of the CAO ecosystem, an advanced understanding is needed of how these different variables of interest interact, influence each other and relate to what happens in the rest of the world. Only limited CAO specific data is available for the use of potential CAO fisheries management, and we identify serious knowledge gaps with regard to fish stock abundance and dynamics, infrastructure requirements, interactions with other economic activities, environmental change, and global and Arctic drivers, predictions on future demand for fish from this region, and institutional capacity to collaborate for managing the stock. However, socio-economic and ecological data and research methods from the adjacent Arctic shelf seas can, with certain reservations, be applied also to the CAO. Furthermore, there are methods available that can allow for informed ecosystem management that enables the minimization of systemic risks even with very limited access to information and data.

8.2. Background

From the perspective of fisheries management, the CAO is largely an "unwritten chapter". The recently signed Agreement puts a moratorium on commercial fishing in the high seas of the Arctic Ocean until sufficient scientific information is available to enable sustainable fishing practices (initially for 16 years). New governance structures, such as a more general regional seas convention and management body, a new regional fisheries management organization (RFMO) or a specific "Ocean Agreement" under the Arctic Council umbrella, have been suggested as possible frameworks to manage potential future fishing in the CAO (Baker & Yeager 2015, Landriault 2018, Niiranen et al. 2018). This chapter is dedicated to identifying the governance and socio-economic data necessary to decide on proper management structures, and possibly carry out sustainable fisheries management, in the future CAO - environmental and ecological conditions allowing. Following the existing CAO-specific literature and more general literature pertaining to sustainable management of marine fish stocks, potential, sustainable fisheries management in the CAO would require access to the following information and data:

1. **Size and distribution of fish stocks and their ecosystem interactions.** For each relevant species, information on current stock sizes/quantities and distribution are necessary, as well as some knowledge about how they may change and, which other variables, such as environmental conditions, biotic interactions and human activities, are likely to influence the stock sizes in the future.
2. **Costs and resource needs (production factors) necessary to potentially be able to exploit these resources.** These include labour, skills, infrastructure, tools, transportation and processing needs, etc., and how they are likely to change due to technological changes and changes in availability of production factors.
3. **Externalities and interactions.** Could the production/harvest of some other resources (non-living resources in the seafloor, new transport routes, new touristic activities etc.) influence fisheries production/harvest? What is the likelihood of externalities affecting production or consumption of the goods potentially produced in the CAO?
4. **State of the demand (local and global) for these resources and how this can be expected to change in the future.** If demand is low compared to production costs, (potential) commercial production in the CAO is unlikely to take place. However, if other sources of food production are likely to become scarcer [e.g. decline of agricultural products in some regions due to climate change (Blanchard et al. 2017)],

demand for fish, and in particular Arctic fish, is likely to increase together with the profitability of those fisheries.

5. **Existing institutional arrangements.** In particular, knowledge of which jurisdiction have the capacity to govern the region or influence its future, for example, through the ability to restrict access or steer resources management. This will indicate whether the CAO fish resources are more likely to be managed as a common pool or open access resource, or under some other type of management institution.
6. **Identification of regional actors of relevance.** Understanding of the countries and indigenous communities engaged in resource extraction, as well as the respective companies operating in the region, including their size (production volumes, revenues etc), will help to identify different ways to enable management and change. This work includes identifying how different countries have ratified treaties, or are participating in relevant governance structures, and identification of individual "keystone actors" in the industry (Österblom et al. 2015).

8.3. Summary of literature searches

To review the existing knowledge and data availability on CAO fisheries management and governance, Web of Science, EU publications (https://publications.europa.eu/en/home) and Google Scholar were searched using a set of relevant keywords/concepts (**Table 8.1**). Only a very limited number of scientific publications (Web of Knowledge) were found using our search criteria, most of which originate from time period 2016-2019 indicating that fishing in the CAO has become a topic of scientific interest rather recently. The same temporal trend was also visible in the case of EU publications. Many of the recent publications discuss the Agreement. Generally, scientists recognize that the opening of CAO and managing its natural resources calls for a focus on regional, instead of national, policies (Landriault 2018), and there is a need for holistic approaches, where the interactions of several sectors and actors are accounted for (Niiranen et al. 2018). No scientific publications were found using the search terms "Central Arctic Ocean fisheries data", "CAO fish catch", and "CAO fisheries value", illustrating that clearly more information is needed on both the CAO fish production potential and the potential socio-economic benefits of fishing in this region. The increasing physical access to the CAO, on the other hand, is addressed in several publications (22 in total).

Table 8.1. Review of existing knowledge and data relevant for potential CAO fisheries governance and management. The brackets contain information on the range of publication years. *Excluding patents and citations from search. (Search date: 9.8.2019)

Search terms	Web of Science	EU publications	Google scholar*
"Central Arctic Ocean"			
AND "fisheries data"	0	7 (2007-2019)	1
AND "fisheries management"	6 (2014-2019)	22 (1999-2019)	444
AND "fisheries governance"	1 (2017)	4 (2015-2019)	51
AND "fish catch"	0	6 (1996-2018)	50
AND "fisheries value"	0	1 (2007)	2
AND "access"	9 (1997-2018)	36 (1990-2019)	5620
AND "economy"	1 (2016)	33 (1990-2019)	832

8.4. Summary of knowledge

Even if CAO-specific data and knowledge are generally lacking, due to the region's remoteness and inaccessibility, there is substantial literature describing the environmental and socio-economic conditions of Arctic shelf seas that partly may be relevant when exploring the potential, sustainable fisheries management in the CAO. For example, several existing bio-economic fisheries models calibrated to Arctic conditions could support the development of new ones particularly adapted to fit CAO conditions, and which could inform several management questions (recent examples include: Diekert et al. 2010, Eide et al. 2013, Kvamsdal et al. 2016, Eide 2017a,b, Richter et al. 2018).

Similarly, existing Arctic assessments (AMAP, Arctic Council 2016), marine spatial planning resources (Edwards & Evans 2017), integrated management methods, tools, or approaches (Hoel & Olsen 2012, Crépin et al. 2017a, Niiranen et al 2018) and sets of indicators (e.g. Crépin et al. 2014) could perhaps be adapted to focus on the CAO. Recent reviews of Arctic fisheries also provide substantial information regarding for example the demand and supply side of this economic activity (Troell et al. 2017). Behavioural experiments focusing on common pool resources with possible threshold in their dynamics could also potentially be adapted to Arctic conditions and provide hints on possible collective action outcomes in the CAO (e.g. Schill et al. 2015). Here we assess to what extent current literature reveals information about the needs identified in **Section 8.1**.

1. **Size and distribution of fish stocks and their ecosystem interactions:** The Arctic is one of the few regions in the world where both the primary productivity and fish production potential is expected to increase in the future (Blanchard et al. 2017, Cabré et al. 2015). According to the latest estimates for sea-ice algae, the foundation for biological production higher up in the marine food web, their production can increase significantly in the marginal ice zone at high latitudes (> 80 degrees, Tedesco et al. 2019). This process could perhaps even extend into certain parts of the CAO, but requires the presence of nutrients which are expected to remain low in the CAO (Tremblay et al. 2015). Furthermore, many fish species follow their temperature niches and move northwards with climate warming (e.g. Frainer et al. 2017). Bio-economic models developed for the Arctic shelf seas highlight, e.g., the importance of accounting for fish (cod) predation on their own young (Wikan & Eide 2004), the role of mesh size in shaping the evolutionary dynamics of the cod species (Diekert et al. 2010), and interactions with aquaculture, and marine reserves (Xuan & Armstrong 2017). These models may be relevant for the CAO as well, despite its remote position, when the sea ice declines further.
2. **Costs and resource needs:** If fish stocks turn out to be sufficiently abundant, melting of the summer sea ice may enable fisheries under similar conditions as those existing in adjacent Arctic shelf seas. The fleets from these adjacent regions typically use different boat sizes and gear types due to different national/institutional constraints (Troell et al. 2017). However, the general trend has been toward larger and fewer fishing vessels being responsible for most of the catches (Troell et al. 2017). Given the distance from the shore, large fishing vessels with the capacity to process fish catches on board, are likely to be the only competitive alternative for the CAO. Yet, they would still need substantial support, such as reliable weather forecasts, iceberg predictions, the capacity to navigate in partially ice-covered waters etc., likely making the costs of fishing in the CAO relatively high (Gascard et al. 2017).
3. **Externalities and interactions:** Fisheries in the CAO are likely to influence – and be influenced by –other economic activities and environmental change. Recent publications highlight the existence and potential impacts of such interconnections (**Figure 8.1**) and introduce tools to better understand their implications (Arctic Council 2016, Crépin et al. 2017a,b, Edwards & Evans 2017, Niiranen et al. 2018). These contributions paint a picture of the potential impacts of complex interactions and highlight the systemic risks and opportunities that these interactions entail, including the potential for rapid, substantial and persistent change. Examples of interactions with fisheries that could be relevant in the CAO include new transport routes, pollution from existing and new extraction activities, impacts of global climate change, ocean acidification, invasive species, and changes in food-web dynamics caused by environmental change (Arctic Council 2016, Crépin et al. 2017a,b, Niiranen et al. 2018).
4. **State of the demand and expected future change:** While the local and regional demand for Arctic fish is limited due to the small human population numbers in the region, there is a substantial global demand for fish products. This demand is likely to evolve in response to climate change and its influence on the productive capacity of food markets on land in the rest of the world, the status of fish stocks elsewhere in

the world, environmental concerns increasing the demand for fish from sustainable fisheries, health concerns promoting an increase of fish in standard diets and demands for feed for animal production (Troell et al. 2017).

5. **Institutional arrangements:** Management of Arctic fisheries builds on international cooperation between the five nations with coasts to the Arctic Ocean [Russian Federation, Norway, Greenland (Kingdom of Denmark), Iceland and the USA], and also with other nations that may want to access these waters – including traditional fishing nations such as Japan and China – and an international group of actors with stakes in the region like the EU. Current management of many of the existing Arctic stocks builds on international collaboration, in particular bilateral agreements like the Russian-Norwegian Barents Sea cod fishery (Eide et al. 2013). Common fish stocks risk to be redistributed due to climate change, which may challenge the existing collaborations when stocks move from one jurisdiction to another or become available to a third actor (Jansen et al. 2016, Pinsky et al. 2018). For example, in response to migratory changes in mackerel stocks in 2007, the Faroe Islands ceased to cooperate with the EU and Norway when setting quotas. However, Hannesson (2014) suggests that quasi-cooperation arrangements between Faeroe Islands and Iceland may have contributed to a healthy stock. While the countries did not officially cooperate, they set much more cautious unilateral quotas than theory would have predicted under non-cooperation.
6. **An identification of regional actors of relevance**: A handful of large fishing companies are responsible for fishing the majority of world's fisheries catch (Österblom et al. 2015), and this is likely to have relevance also for the CAO. Methods for identifying such "keystone" actors include reviews of company annual reports, interviews, company audits and presentations, industry trade data, country- and region-specific quota allocations and catch records. Data that can be used are collected by e.g. FAO, the Seaaroundus Project and Global Fishing Watch (GFW) (Österblom et al. 2015). None of the existing information has ever been compiled with a specific focus on the CAO.

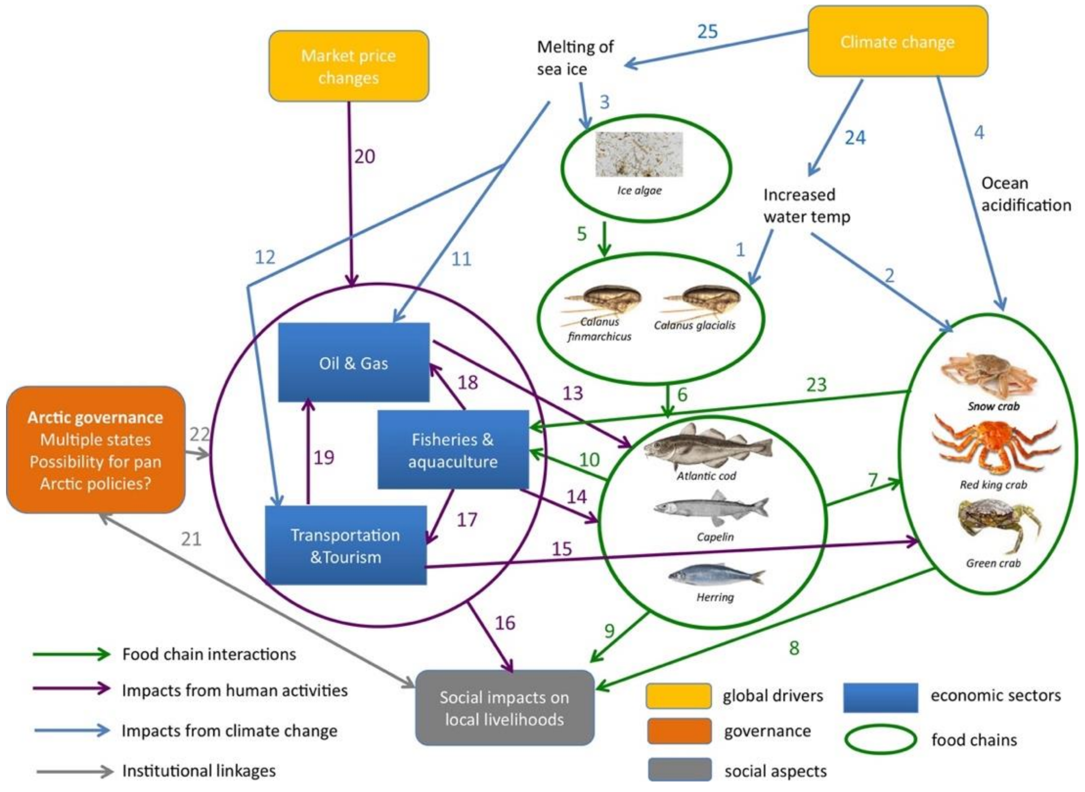


Figure 8.1. An example of social-ecological interactions of an Arctic ecosystem (Figure from Crépin et al. 2017a).

8.5. Critical gap analysis

The gap analysis between the data needed to potentially achieve sustainable stock management (**Section 8.1**), and the actual knowledge (**Section 8.3**) reveals serious lack of both ecological and socio-economic data (**Table 8.2**). In particular, we identified knowledge gaps with regard to fish stock abundance and dynamics, infrastructure requirements to cope with potential fishing activities, interactions with other economic activities, environmental change, and global and Arctic drivers, predictions on future demand for CAO fish, and institutional capacity to collaborate for managing the stocks. In some cases, the raw data from individual aspects or analysis are in place, but data analysis is needed. However, data from other systems, e.g. from the Arctic shelf seas, can be useful when designing potential fisheries management in the CAO. In order to ensure sustainable fisheries and ecosystem management in a vulnerable open access region, such as the CAO, it is essential to not only have information on the target species, but also to account for the potential interactions between fisheries, environment and the different economic sectors. Such holistic approach to management is the only way to understand what is needed to maintain sufficient resilience, and avoid collapses in possible future CAO fisheries, when facing external pressure from climate and resource extraction. Policies and management structures should be implemented to safeguard potential fisheries as part of a sustainable CAO system. Obtaining enough information to be able to put together the essential parts of this puzzle should be a key priority for EFICA.

The lack of data and information hinders a complete assessment of conditions for potential, sustainable management of CAO fisheries. However, taking a holistic approach – building for example on Arctic Council (2016) and Crépin et al. (2017) – implies that informed management can be possible even with very limited access to information and data. Such approach can contribute to identifying systemic risk, and thus define conservative boundaries for precautious or even safe management, which is likely to be the best approach when facing large uncertainties. These limits can be subsequently updated when appropriate information becomes available. A holistic approach can also help target areas where information and data collection should be prioritized. It can immediately inform the potential consequences of some new phenomenon by allowing to track its potential impacts throughout the system and identify threats or opportunities for sustainable development.

With this perspective, and based on the gap analysis performed in this chapter, we suggest that priority areas for data and research related to governance and socio-economic development of potential fisheries in the CAO focus on:

- Assessing the dominant fish species present in the CAO, a rough estimate of their potential stocks, distribution and expected food chain dynamics (using EFICA field and modelling data and synthesis of existing literature).
- Assessing possible interactions between potential CAO fisheries and other economic activities, as well as with the Arctic environment (using synthesis of existing findings and modelling)
- Assessing the keystone actors (both states and private sectors) in the CAO (using the methodology presented in Österblom et al. 2015).
- Building a simplified "systems picture" (e.g. **Figure 8.1**) including important interactions with other economic activities and the environment, including local communities to understand which drivers affect potential CAO fisheries, directly and indirectly, based on the above assessments (further develop and synthesize information gathered in Arctic Council 2016, ACCESS, and other similar exercises and adapt them to the CAO).
- Identifying systemic risk emerging from the "systems picture" through chains of positive feedback loops, critical thresholds, accumulating impacts, slow processes, and other factors influencing system resilience and sustainability (using, for example, causal loop diagrams, scenario analysis and simplified modelling).
- Assessing the institutional capacity to collaborate around CAO management in relation to potential triggers of systemic risk (using causal loop diagrams, scenario analysis, simplified modelling).
- Use the risk assessment to guide further data collection, modelling exercises and experiments to continuously refine the systems picture (synthesis of the activities above).

Table 8.2. Critical gap analysis for variables relevant for governance and socio-economic development of potential fisheries in the CAO. Estimate of severity of the knowledge gap: 0 = no knowledge, 1 = serious lack of knowledge, 2 = insufficient knowledge, 3 = sufficient knowledge available for the purpose indicated in column 2.

Variable	Why the variable is necessary to evaluate possibilities for potential future fisheries	Estimate of severity of the knowledge gap	What data needs to be collected to decrease the gap?
Fish species present, stock abundance in the CAO	To estimate the extent of the available resource and define MSY	0-1	Fish species present, stock abundance
Interaction with other sectors (including externalities)	To understand possible synergies and conflicts with other CAO activities, such as shipping, tourism and oil/gas interests	1-2	Draw knowledge from examples from other regions; Potential use of CAO by multiple sectors should be mapped; Spatial modelling frameworks and system models from past projects (e.g., Arctic ACCESS, Edwards & Evans 2017, Crépin et al. 2017a,b) to be parameterized with CAO specific data
Interaction between potential fisheries and the environment	Environmental change (e.g., climate change, ocean acidification, invasive species and oil spills) can influence reproduction, feeding patterns and survival rate of fish species. Fish stocks can also impact their environment e.g. through their feeding behaviour.	1-2	General features of environmental impacts on potential fisheries are well studied in other ecosystems including adjacent Arctic waters; Some of these impacts like oil spills may behave very differently in ice-covered waters (e.g. Wilkinson et al. 2017); Very little is known about the specificity of those impacts in the CAO
Costs of potential fishing and resource needs (i.e., production factors)	To estimate the potential profitability of a CAO fishery and the possibility that it would or not take place spontaneously	2	Assessment of technological requirements to potentially fish safely in the CAO; Estimation of the costs of labour, infrastructure, transportation and technology; Required technology is not available, costs for technical development must be estimated along with success chance (see point on technology)
Access	To understand physical limits for possible fisheries expansion to CAO	2-3	Improved understanding on ice melt and potential shipping routes
Technology available and technical needs	To understand the fishing impact on the environment and fish, and to understand feasibility and costs of potential fishing	2	Projections on future ice and weather conditions; Estimating environmental effects of the current technology where relevant for the CAO
Fish price and demand (current/future, local/global)	To estimate the potential profitability of a CAO fishery and the possibility that it would or would not take place spontaneously	2-3	Data on the price development of key commercial fish species available; Some data lacking regarding demand that is not accounted by the market (e.g. from non-commercial fisheries and indigenous peoples)
Current governance structures and limitations concerning the CAO natural resource use	To understand if potential fishing can be managed sustainably under existing mechanisms	2	Data on formal governance structures needs to be synthesized and analyzed where relevant for CAO; Data on informal governance/management structures need to be collected and analyzed
Potential key actors in potential fisheries	To understand the magnitude of potential fishing pressure, and to provide information for the most effective governance measures	2	Some data on actors is available, i.e., via scientific publications (e.g. Österblom et al. 2015); Analysing International trade data on capture fish, and other industry reports (including annual reports from companies); Data needs to be analysed considering the access to CAO specifically; Using Global Fishing Watch (GFW) to identify vessels, fishing effort, and ownership
Existing Conventions (e.g. UNCLOS) relevant for possible fishing in the CAO	To understand the potential and limitations set by current conventions	3	Data available, some level of synthesis may be needed

Chapter 9. Recommendations on research priorities and the next steps

Pauline Snoeijs-Leijonmalm (SU), Hauke Flores (AWI)

9.1. Chapter summary

Research priorities comprise the collection and analysis of primary data in the CAO, and – to a limited extent – from adjacent waters through collaborations between the Signatories of the Agreement. Further research priorities include an evaluation of ecosystem vulnerability, social-ecological analyses, i.e., recognizing the close and often complex interactions between humans and nature, and recommendations for governance of the CAO. Fulfilling the 14 specific research priorities mentioned in this chapter to "sufficient knowledge available" would make the application of an Ecosystem Approach to Management for the CAO possible.

9.2. Ecosystem Approach to Management

Unregulated fishing is a global threat to the marine environment, and to the sustainable use of marine resources. The EU Common Fisheries Policy (CFP) states that the EU, as a large maritime power and as the world's biggest market for seafood, actively promotes better international governance across the world's seas and oceans to keep them clean, safe and secure (https://ec.europa.eu/fisheries/cfp_en). Thus, the EU has a large responsibility to further engage in the conservation and possible future sustainable use of the fish stocks in the CAO. The CFP is moving towards an Ecosystem Approach to Management, which should be adopted as a basis for the future governance of the High Seas of the Arctic Ocean. The CAO is a particularly sensitive ecosystem that requires a carefully designed approach when moving from the scientific mapping and surveying to the potential harvesting of fisheries resources in the future. Major challenges in the case of the CAO are: (1) the general lack of data on the CAO fish stocks and their role in the Arctic food webs, (2) constraints for scientific cooperation, including data and scientific sample exchange, between countries, and (3) the cumulative effect of environmental, biotic and human stressors in an era of rapid climate warming.

The general approach of the CFP is to lay down rules ensuring that fisheries are sustainable ("Maximum Sustainable Yield", MSY) and do not damage the marine environment ("Good Environmental Status"). However, such analyses are not possible today for the CAO due to largely unknown fish stocks and ecosystem status. When the impact of fishing on the marine environment is not fully understood, the CFP adopts a precautionary approach, which recognises the impact of human activity on all components of the ecosystem. This is also the approach taken in the Agreement. Since we currently do not have appropriate and reliable sentinels for ecosystem health in the CAO, data should be collected for a future Ecosystem Approach to Management in the CAO. For this we need to (1) describe the ecoregion (an ecologically and geographically defined area), identify the impacts of pressures and drivers on key ecosystem components by collecting new basic ecological data on the CAO fishes, including environmental and food-web interactions, (2) define MSY options and reference points on fish biomass changes in productivity by stock assessment, using the new data in modelling, (3) collect and analyse relevant socioeconomic data that enables us to summarize the possible future fleet activity impacts on fishes and species trade-offs between fleets (**Figure 9.1**).

MSY focuses only on the renewal capacity of the stock and does not consider any costs associated with harvesting, food web interactions or environmental change. A more holistic approach picturing the CAO as a SES where socio-economic activities are tightly interlinked with the geophysical environment and ecosystem dynamics would provide better tools to identify critical risks, leverage points for change and indicators of the three dimensions of sustainability (social, economic and environmental). Such approaches have been implemented for the whole Arctic Ocean in Arctic Council (2016), Crépin et al. (2017) and Niiranen et al. (2018), and could be further adapted to the specific conditions of the CAO using existing data and results from the planned EFICA expeditions.

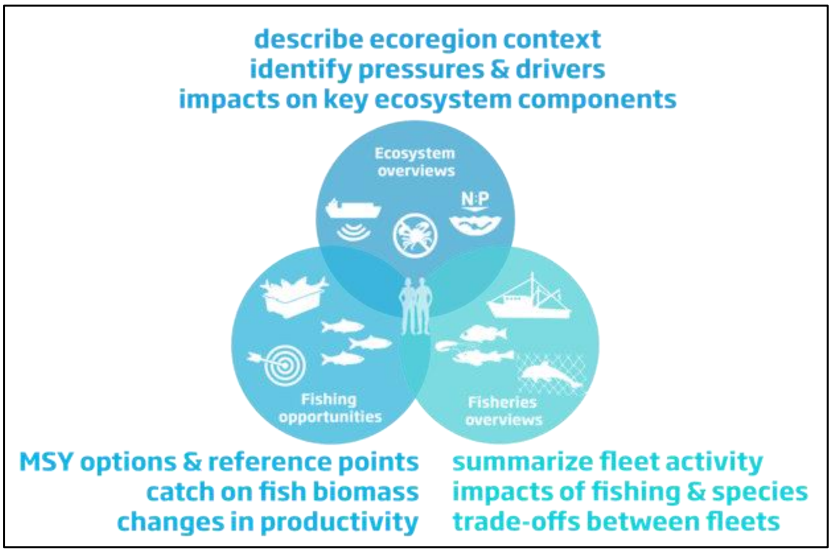


Figure 9.1. The three main inputs to support an Ecosystem Approach to Management. Figure from ICES (www.ices.dk)

9.3. Holistic gap analysis

The critical gap analysis tables in **Chapters 2-8** are summarized in **Figure 9.2**, using a set-up covering the whole CAO ecosystem. This figure highlights that the knowledge gaps for the CAO are enormous and obstruct any quantitative analyses of its fish stocks. This agrees with the conclusions from the Fifth FiSCAO Report (FiSCAO 2018). While data for the physical environment in the CAO (oceanography, bottom topography and ice-cover dynamics) would be sufficient for fish stock modelling and assessment, there is a massive lack of biological and ecological data. The CAO is not a closed system and some aspects of the shelf seas are of high relevance for the CAO, notably connectivity of fish stocks and fish species moving north with climate warming. Scientific research and monitoring programs are established in the shelf seas, and new data are constantly being produced.

Fish stock data are available from scientific projects and monitoring programs for some of the shelf seas (Barents Sea, Bering Sea, and to a lesser extent for the Beaufort Sea and the Chukchi Sea). Data exist also for the Russian shelf Seas (Kara Sea, Laptev Sea, East Siberian Sea), but these data are not internationally available, while for the areas north of Canada/Greenland data are missing; they do not exist because of the severe ice conditions there. More data from all shelf seas may be hidden in reports that are not publicly accessible. We recommend to make current knowledge generally available by translating key publications and identification of valuable data reports.

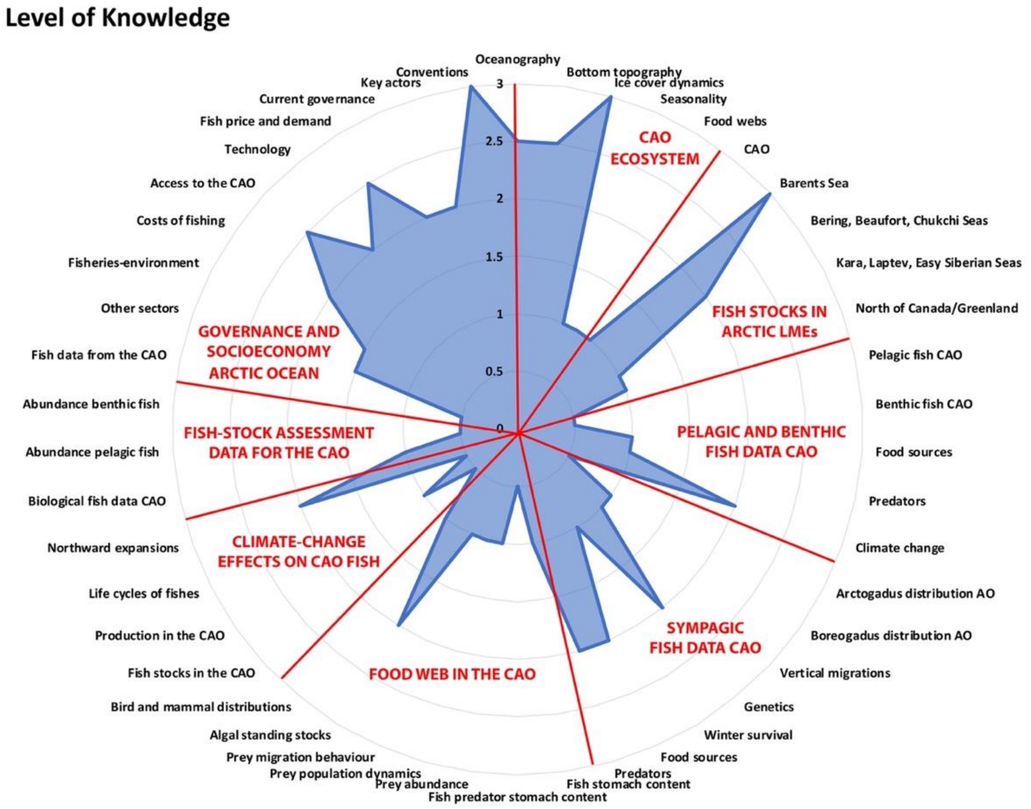


Figure 9.2. Radar chart summarizing the gap analyses presented in this Report (**Tables 2.3, 3.2, 4.3, 5.3, 6.2, 7.2, 8.2**). On the axis the estimates of the severity of the knowledge gaps are given: 0 = no knowledge, 1 = serious lack of knowledge, 2 = insufficient knowledge, 3 = sufficient knowledge available. The larger the blue area is in the direction of a specific subject, the smaller the relative knowledge gap on this subject.

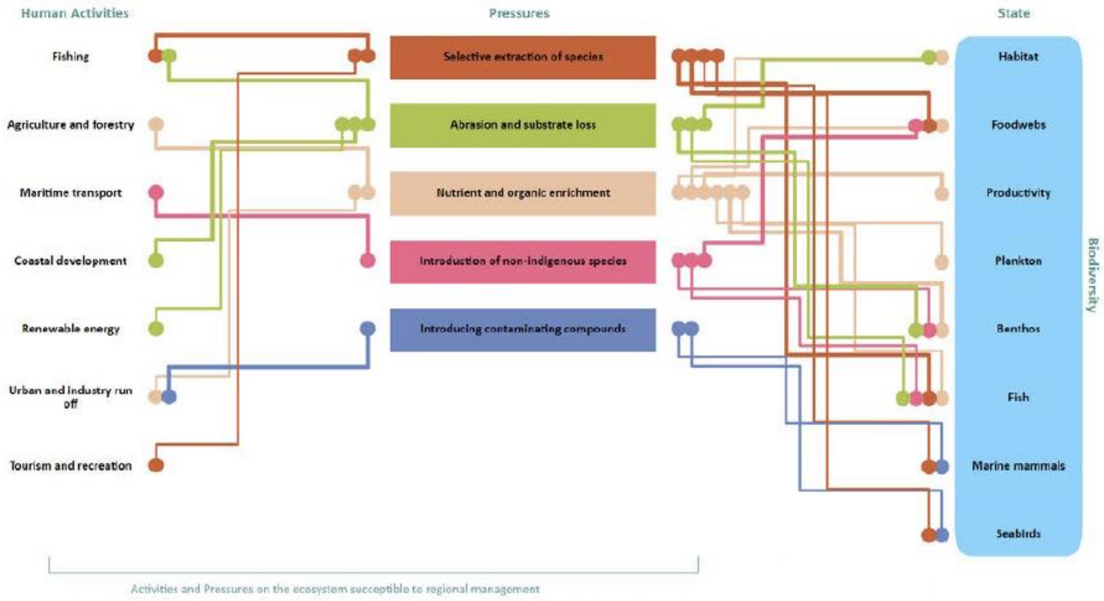


Figure 9.3. Set-up of a vulnerability analysis by ICES that could be used as a model for further work within EFICA. This figure is taken from the ICES Ecosystem Overviews - Baltic Sea Ecoregion, Version 2 (21 January 2019). Please, note that the Baltic Sea is one of the World´s best studied marine areas. whereas for the CAO and High Seas area information is sparse. See also: http://www.ices.dk/community/advisory-process/Pages/Ecosystem-overviews.aspx

9.4. Recommendations on research priorities

Research priorities comprise the collection and analysis of primary data in the CAO and – to a limited extent (genetic samples) – also from adjacent waters (**Table 9.1**, Items 1-7, 10), evaluation of ecosystem vulnerability, social-ecological system analyses that combine the ecological and socio-economic knowledge, and recommendations for governance of the CAO (**Table 9.1**, Items 8-9, 11-14). Fulfilling the 14 specific research priorities to "sufficient knowledge available" could make the potential, future application of an Ecosystem Approach to Management possible for the CAO as well as a more holistic approach to potential management that takes into account social, economic and environmental dimensions of sustainability.

Some of these research priorities can complement each other to improve system knowledge. For example, priorities 1, 2, 3 and 6 all relate to ecosystem dynamics and are all needed to improve knowledge of the dynamics of the marine ecosystem in the CAO, which can inform about priority 5 on ecosystem productivity. These ecosystem dynamics are then influenced by 4 and 7, which are also necessary to understand possible trends in future ecosystem productivity. Vulnerability analysis (priority 8) builds on ecosystem data (1-7). Although some desktop product can be created from existing literature, data and from studies related to areas nearby the CAO (e.g. priorities 10-12), strategically targeted information gathering could have the potential to substantially decrease the ranges of uncertainties associated with this type of assessment. Vulnerability analysis should also take into account pressures from existing and potential socio-economic activities (13) and governance (9, 14), which could exercise as much influence on the outcome as the natural dynamics.

Table 9.1. Summary of research priorities (not in any specific order of importance) relevant for the potential, future application of an Ecosystem Approach to Management for the CAO. Estimate of severity of the knowledge gap: 0 = no knowledge, 1 = serious lack of knowledge, 2 = insufficient knowledge, 3 = sufficient knowledge available for the purpose indicated in column 2. MSY = Maximum Sustainable Yield.

Nr	Variable	Why the variable is necessary to evaluate possibilities for potential future fisheries	Estimate of severity of the knowledge gap today	Necessary data collection
Data from the CAO				
1	**Sympagic fish** Species, density, biomass, demography, life-history strategies in different sub-areas, seasons and years	Model and assess existing fish stocks in the CAO, define MSY	**0-1** Four papers, in summer juvenile *Boreogadus* Two papers, in winter both *Boreogadus* and *Arctogadus* (very few quantitative data)	**Icebreaker expeditions** Acoustics Deep-sea cameras Scientific samples
2	**Pelagic fish** Species, density, biomass, demography, life-history strategies in different sub-areas, seasons and years	Model and assess existing fish stocks in the CAO, define MSY	**0-1** One paper (manuscript), species not identified	**Icebreaker expeditions** Acoustics Deep-sea cameras Scientific samples
3	**Benthic fish** Species, density, biomass, demography, life-history strategies in different sub-areas, seasons and years	Model and assess existing fish stocks in the CAO, define MSY	**0-1** Single observations, no systematic study. Non-commercial species (eelpouts, sculpins), but also perhaps commercial Greenland halibut, *Reinhardtius hippoglossoides*	**Icebreaker expeditions** Deep-sea cameras Scientific samples
4	**Environmental variables** Ice cover, temperature, salinity, nutrients, water currents, bottom topography in different sub-areas, seasons and years	Extend the results obtained in 1-3 to a larger area by modelling	**2-3** Good oceanographic and bottom topography data are available from *RV Oden* and *RV Polarstern*, but not for all CAO sub-areas and seasons	**Icebreaker expeditions** Measure while fish surveys are carried out **Satellite data** Ice cover
5	**Ecosystem productivity** Primary, secondary and tertiary production in different sub-areas, seasons and years	Understand and predict the MSY the CAO ecosystem could produce	**2** There are primary productivity papers and also zooplankton biomass studies – a good summary of this has been made by the WGICA group	**Icebreaker expeditions** Measure while fish surveys are carried out
6	**Food-web interactions** Stomach analyses, stable isotope analyses, fatty acids	Model and understand how the existing fish stocks depend on biotic interactions	**1** There are some papers on the biodiversity of food items (sympagic amphipods, zooplankton) and predators (seals, beluga whales, narwhals), but practically nothing about food-web interactions	**Icebreaker expeditions** Measure while fish surveys are carried out
7	**Climate warming impacts** Effects of increased water temperature on ocean circulation and organisms. Compare areas with and without ice cover in the CAO (summer). Study the effects of melting of glaciers and the sea ice (freshwater input into the CAO). Ocean acidification	To model and understand how the existing fish stocks may change in the near future as a result of changes in the physical, chemical and biotic environment with climate warming	**1-2** On the physical side there are a lot of papers, e.g. changes in ice cover and ocean circulation, but practically nothing on organisms	**Icebreaker expeditions** Measure while fish surveys are carried out **Satellite data** Ice cover

8	**Vulnerability analysis** (*cf.* Figure 9.3)	Evaluation of fish stocks in relation to other pressures to decide which conservation measures are necessary and if any sustainable fisheries could be allowed	**0** No papers found (fish stocks unknown)	**Desk studies** Data for 1-7 is necessary Literature studies of other pressures
9	**Evaluation of governance structures**	To decide how the CAO ecosystem could be managed	**2** In the past years a number of papers in this field have been published about the High Seas / CAO in the fields of law, management, etc.	**Desk studies** Data for 1-8 is necessary Literature studies of other pressures Literature studies of socio-economy, political agreements, etc. (*cf.* Table 8.2)
Data from the Arctic shelf seas				
10	**Genetic fish studies** of relevance for the CAO	Fish stock health and survival	**1** Some studies exist on *Boreogadus* and *Arctogadus* but not from the CAO	**Pan-Arctic scientific cooperation:** Assess connectivity of populations, identify spawning areas of different populations All shelf seas and the CAO, integrate genetic methods between countries
11	**Ecological fish studies** of relevance for the CAO	To assess connectivity of populations and to identify which fish species are moving northward with climate change - towards the CAO?	**2-3** Many research papers and reports (Barents Sea, Chukchi Sea, Beaufort Sea)	**Desk studies** Ecological linkages between potentially harvestable fish stocks of the CAO and the shelf seas (but first it is necessary to know which fish we have in the CAO)
12	**Ecosystem change** (physical, chemical, biotic) of relevance for the CAO	To assess the ecological effects of climate warming and ocean acidification	**2-3** Oceanographic, productivity and food-web data exist	**Desk studies** Some of this knowledge could be extrapolated to the CAO but most of the CAO (deep nutrient-poor basins) is very different from the shelf seas (coastal, partly nutrient-rich)
13	**Pressures** of relevance for the CAO	Human activities, including long-distance pollution, spatial extension (i.e., northwards movement) of different economic sectors and key actors,	**1-2**	**Desk studies**
14	**Governance** of relevance for the CAO	Governance is under national jurisdiction	**2**	**Desk studies**

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Appendix 1. Fish species found in the Central Arctic Ocean and adjacent waters, with data on depth range, global distribution and human use. The data portal www.fishbase.org was used to acquire more detailed knowledge on fish distribution and ecology. * = value modified according to newer literature. The 13 temperate or boreal taxa of commercially harvested finfish with a potential to expand their distribution into the Arctic Ocean according to Hollowed et al. (2013) are indicated in red and the 17 species recorded in the CAO are indicated by a green background.

#	**Species**	**Depth range** (fishbase.org)	**Distribution** (fishbase.org)	**Human use** (fishbase.org)	**Reported presence in the Arctic Ocean**	**Source**
1	*Acantholumpenus mackayi*	0-200 m	Atlantic-Arctic	None		Andriyashev & Chernova (1996), Mecklenburg et al. (2011, 2018)
2	*Alepocephalus agassizii* (Agassiz' slickhead)	600-2500 m	Atlantic-Boreal	Potentially commercial	Baffin Bay	Jørgensen et al. (2005)
3	*Amblyraja hyperborea* (Arctic skate)	300-1500 m	Boreal-Arctic	None	CAO, Canada Basin, Baffin Bay, Barents Sea, Beaufort Sea, Greenland Sea, Hudson Bay, Kara Sea, Laptev Sea, Norwegian Sea, Siberian Sea	Mecklenburg et al. (2002), Stein et al. (2005), Lynghammar et al. (2013)
4	*Amblyraja radiata* (starry ray)	25-440 m	Atlantic-Arctic	Low commercial interest	CAO, Canada Basin, Baffin Bay, Barents Sea, Greenland Sea and coast, Hudson Bay, Norwegian Sea, White Sea	Lynghammar et al. (2013)
5	*Ammodytes hexapterus* (Pacific sand lance)	0-275	Pacific-Arctic	Commercial	Bering Sea, Chukchi Sea, Canadian Arctic Archipelago, Beaufort Sea	Suzuki et al. (2015), Kono et al. (2016), Falardeau et al. (2017)
6	*Anarhichas denticulatus*	60-1700 m	Atlantic-Arctic	Recreational fishing		Andriyashev & Chernova (1996), Mecklenburg et al. (2011, 2018)
7	*Anarhichas orientalis*	0-100 m	Pacific-Arctic	None	Chukchi Sea, Beaufort Sea	Mecklenburg et al. (2011)
8	*Anisarchus medius* (stout eelblenny)	10-300	Boreal	None	CAO	FiSCAO (2017), Andriyashev & Chernova (1996), Mecklenburg et al. (2011, 2018)
9	*Arctogadus glacialis*	0-1000 m	Arctic	Low commercial interest	CAO	FiSCAO (2017), Mecklenburg et al. (2011), see Table 4.2
10	*Artediellus atlanticus* (Atlantic hookear)	35-900 m	Atlantic-Arctic	No data	CAO, Siberian Sea, Chukchi Sea, Kara Sea, Laptev Sea, Beaufort Sea, Baffin Bay	FiSCAO (2017), Mecklenburg et al. (2011)
11	*Artediellus scaber*	0-290 m	Boreal-Arctic	No data	Barents Sea, Siberian and American coastal seas	Mecklenburg et al. (2011), Rand & Logerwell (2011)
12	*Aspidophoroides olrikii*	7-520 m	Boreal-Arctic	No data	Wide distribution, Beaufort Sea	Mecklenburg et al. (2011), Rand & Logerwell (2011), Suzuki et al. (2015)

13	*Bathylagus euryops* (goiter blacksmelt)	500-3237 m	Atlantic-Boreal	None	Baffin Bay	Jørgensen et al. (2005), Møller et al. (2010)
14	*Bathyraja spinicauda* (spinetail ray)	140-1463 m	Atlantic-Arctic	None	Barents Sea, Hudson Bay, Norwegian Sea	Mecklenburg et al. (2011), Lynghammar et al. (2013)
15	*Benthosoma glaciale* (glacier lanternfish)	0-1407 m	Wide (Atlantic-tropical-Arctic)	Potentially commercial	Kara Sea, Baffin Bay, Coast of Spitsbergen	References in Mecklenburg et al. (2011)
16	*Blepsias bilobus*	0-250 m	Pacific-Boreal	Recreational fishing	Bering Sea, Chukchi Sea	Mecklenburg et al. (2011)
17	*Boreogadus saida* (Polar cod)	0-4000 m*	Arctic	Low commercial interest *	CAO, Circumpolar	FiSCAO (2017), David et al. (2016), see Table 4.2
18	*Bythites fuscus* (Arctic brotula)	?-526 m	Atlantic-Boreal	None		Andriyashev & Chernova (1996), Mecklenburg et al. (2011, 2018)
19	*Careproctus micropus*	100-1800 m	Arctic	No data	Continental slopes	Mecklenburg et al. (2011)
20	*Careproctus reinhardti* (sea tadpole)	75-1750 m	Atlantic-Arctic	None	CAO, Continental slopes	FiSCAO (2017), Mecklenburg et al. (2011)
21	*Centroscymnus coelolepis*	150-3700 m	Wide (tropical-Boreal)	Low commercial interest	Baffin Bay	Møller et al. (2010)
22	*Centroscymnus coelolepis* (Portugese dogfish)	400-2000 m	Cosmopolitan	Low commercial interest	Baffin Bay	Lynghammar et al. (2013)
23	*Cetorhinus maximus* (basking shark)	0-2000 m	Cosmopolitan	Commercial	White Sea, Barents Sea, Norwegian Sea, Greenland coast	Mecklenburg et al. (2011), Lynghammar et al. (2013)
24	*Clupea harengus* (Atlantic herring)	0-364 m	Temperate-Boreal	Highly commercial	Barents Sea	Hollowed et al. (2013)
25	*Clupea pallasii* ssp. *pallasii* (Pacific herring)	0-475 m	Temperate-Boreal	Highly commercial	Bering Sea, Chukchi Sea	Mecklenburg et al. (2011), Kono et al. (2016)
26	*Coregonus autumnalis* (Arctic cisco)	Coastal	Arctic	Commercial		Andriyashev & Chernova (1996), Mecklenburg et al. (2011, 2018)
27	*Coregonus laurettae* (Bering cisco)	Coastal	Pacific-Arctic	Subsistence fisheries		Andriyashev & Chernova (1996), Mecklenburg et al. (2011, 2018)
28	*Coregonus muksun* (muksun)	Coastal	Arctic	Highly commercial		Andriyashev & Chernova (1996), Mecklenburg et al. (2011, 2018)
29	*Coregonus nasus* (broad whitefish)	Coastal	Pacific-Arctic	Commercial		Andriyashev & Chernova (1996), Mecklenburg et al. (2011, 2018)

30	*Coregonus pidschian* (humpback whitefish)	Coastal	Boreal-Arctic	Commercial		Andriyashev & Chernova (1996), Mecklenburg et al. (2011, 2018)
31	*Coregonus sardinella* (sardine cisco)	Coastal	Arctic	Commercial		Andriyashev & Chernova (1996), Mecklenburg et al. (2011, 2018)
32	*Coryphaenoides rupestris* (roundnose grenadier)	180-2600	Atlantic-Boreal	Commercial	Baffin Bay	Jørgensen et al. (2005)
33	*Cottunculus microps* (polar sculpin)	165-1342 m	Atlantic-Boreal	None	CAO, Chukchi Sea	FiSCAO (2017), Mecklenburg et al. (2011)
34	*Cyclopteropsis mcalpini* (Arctic lumpsucker)	174-? m	Boreal-Arctic	No data		Andriyashev & Chernova (1996), Mecklenburg et al. (2011)
35	*Eleginus gracilis* (saffron cod)	0-300 m	Pacific-Boreal	Highly commercial	Alaska coast, Bering Sea, Chukchi Sea	Norcross et al. (2010), Kono et al. (2016)
36	*Eleginus nawaga*	Coastal?	Boreal-Arctic	Commercial		Andriyashev & Chernova (1996), Mecklenburg et al. (2011, 2018)
37	*Entelurus aequoreus* (Atlantic snake pipefish)	5-100 m	Atlantic-Arctic	None	Greenland Sea, coast of Svalbard, Barents Sea	Fleischer et al. (2007), references in Mecklenburg et al. (2011)
38	*Eumesogrammus praecisus* (fourline snakeblenny)	5-400 m	Boreal-Arctic	None	Beaufort Sea	Andriyashev & Chernova (1996), Mecklenburg et al. (2011, 2018)
39	*Eumicrotremus &riashevi* (pimpeled lumpsucker)	20-83 m	Pacific-Boreal	No data	Bering Sea, Chukchi Sea	Mecklenburg et al. (2011)
40	*Eumicrotremus derjugini* (leatherfin lumpsucker)	50-930 m	Arctic	No data	Wide distribution	Mecklenburg et al. (2011), Rand & Logerwell (2011)
41	*Eumicrotremus spinosus* (Atlantic spiny lumpsucker)	30-400 m	Temperate-Arctic	No data	Canadian Arctic Archipelago, northern Greenland, Kara Sea	Mecklenburg et al. (2011)
42	*Gadus (Theragra) chalcogrammus*	30-400 m	Pacific-Boreal	Highly commercial	Beaufort Sea	Logerwell et al. (2011), Mecklenburg et al. (2011)
43	*Gadus macrocephalus* (Pacific cod)	100-400 m	Pacific-Boreal	Highly commercial	White Sea, Bering Sea, Chukchi Sea, coastal Arctic Areas, Beaufort Sea	Mecklenburg et al. (2011), Kono et al. (2016)
44	*Gadus morhua* (Atlantic cod)	0-600 m	Atlantic-Boreal	Highly commercial	Northern Fram Strait	Ingvaldsen et al. (2017)

45	*Gaidropsarus argentatus* (Arctic rockling)	150-2260 m	Atlantic-Arctic	Commercial	Barents Sea, Baffin Bay	Mecklenburg et al. (2011)
46	*Gaidropsarus ensis (threadfin rockling)*	0-2000 m	Atlantic-Boreal	None	Barents Sea, Baffin Bay	Mecklenburg et al. (2011)
47	*Gymnelus hemifasciatus* (halfbarred pout)	9-175 m	Arctic	None	Bering Sea	Mecklenburg et al. (2011)
48	*Gymnelus retrodorsalis* (Aurora unernak)	8-418 m	Atlantic-Arctic	None		Mecklenburg et al. (2011)
49	*Gymnelus viridis* (fish doctor)	0-320 m	Pacific-Arctic	None	Beaufort Sea	Mecklenburg et al. (2011), Rand & Logerwell (2011)
50	*Gymnocanthus tricuspis* (Arctic staghorn sculpin)	0-451 m	Temperate-Arctic	No data	Circumpolar	Mecklenburg et al. (2011), Rand & Logerwell (2011), Suzuki et al. (2015)
51	*Gymnocathus tricuspis*	0-451 m	Atlantic-Arctic	None	Bering Sea, Chukchi Sea	Kono et al. (2016)
52	*Hippoglossoides platessoides* (American plaice)	10-3000 m	Atlantic-Boreal	Highly commercial		Mecklenburg et al. (2011)
53	*Hippoglossoides robustus* (flathead sole)	0-1050	Pacific-Arctic	Commercial	Beaufort Sea, Bering Sea, Chukchi Sea	Rand & Logerwell (2011), Mecklenburg et al. (2011), Kono et al. (2016)
54	*Hypomesus olidus*	Coastal	Boreal-Arctic	Commercial		Andriyashev & Chernova (1996), Mecklenburg et al. (2011, 2018)
55	*Icelus bicornis* (twohorn sculpin)	0-930 m	Temperate-Arctic	No data	Circumpolar	Mecklenburg et al. (2011)
56	*Icelus spatula* (spatulate sculpin)	12-930 m (	Boreal-Arctic	No data	Circumpolar	Mecklenburg et al. (2011), Rand & Logerwell (2011)
57	*Lamna nasus* (porbeagle)	0-715 m	Cosmopolitan	Commercial	Barents Sea, Norwegian Sea, Greenland coast	Lynghammar et al. (2013)
58	*Leptagonus decagonus* (Atlantic poacher)	0-930 m	Atlantic-Arctic	No data	Wide distribution	Mecklenburg et al. (2011)
59	*Leptoclinus maculatus* (daubed shanny)	2-607 m	Temperate-Arctic	None	Beaufort Sea	Andriyashev & Chernova (1996), Mecklenburg et al. (2011, 2018)
60	*Lethenteron camtschaticum*	0-50 m	Pacific-Boreal	Commercial	Arctic (unspecified)	Mecklenburg et al. (2011), Lynghammar et al. (2013)
61	*Limanda aspera* (yellowfin sole)	0-700 m	Pacific-Arctic	Highly commercial	Bering Sea, Chukchi Sea	Mecklenburg et al. (2011), Yeung & Yang (2014), Kono et al. (2016)

62	*Limanda proboscidea* (longhead dab)	0-160 m	Pacific-Arctic	No data		Mecklenburg et al. (2011)
63	*Limanda sakhalinensis* (sakhalin sole)	10-360	Pacific-Boreal	Low commercial interest		Mecklenburg et al. (2011)
64	*Liopsetta glacialis*	0-90 m	Boreal-Arctic	Low commercial interest		Andriyashev & Chernova (1996), Mecklenburg et al. (2011, 2018)
65	*Liparis bathyarcticus* (nebulous snailfish)	400-647 m	Pacific-Arctic	None	Circumpolar, slope and shelves	Mecklenburg et al. (2011)
66	*Liparis fabricii* (gelatinous snailfish)	12-1800 m	Atlantic-Arctic	None	CAO, Circumpolar, slope and shelves, Beaufort Sea	FiSCAO (2017), Mecklenburg et al. (2011), Rand & Logerwell (2011), Suzuki et al. (2015)
67	*Liparis gibbus* (variegated snailfish)	0-647 m	Boreal-Arctic	None	Circumpolar, slope and shelves, Beaufort Sea	Mecklenburg et al. (2011), Suzuki et al. (2015)
68	*Liparis tunicatus* (kelp snailfish)	0-620 m	Boreal-Arctic	None	Circumpolar, slope and shelves	Mecklenburg et al. (2011)
69	*Lumpenus fabricii* (slender eelblenny)	0-235 m	Boreal-Arctic	None	Beaufort Sea	Andriyashev & Chernova (1996), Mecklenburg et al. (2011, 2018)
70	*Lycenchelys kolthoffi*	202-930 m	Atlantic-Arctic	None		Mecklenburg et al. (2011)
71	*Lycenchelys muraena*	350-1700 m	Arctic	None		Mecklenburg et al. (2011)
72	*Lycenchelys platyrhina*	?-1848 m	Arctic	None		Mecklenburg et al. (2011)
73	*Lycodes adolfi* (Adolf's eelpout)	1371-1880 m	Atlantic-Boreal	None	CAO, Svalbard slope	FiSCAO (2017), Byrkjedal et al. (2011), Mecklenburg et al. (2011)
74	*Lycodes esmarkii* (greater eelpout)	251-1090 m	Atlantic-Boreal	None		Mecklenburg et al. (2011)
75	*Lycodes eudipleurostictus* (doubleline eelpout)	25-1187 m	Arctic	None		Mecklenburg et al. (2011)
76	*Lycodes frigidus*	475-3000 m	Atlantic-Arctic	None	CAO, Canada Basin	Stein et al. (2005), Mecklenburg et al. (2011)
77	*Lycodes gracilis*	94-113 m	Atlantic-Boreal	None		Mecklenburg et al. (2011)
78	*Lycodes jugoricus* (shulupaoluk)	9-90 m	Arctic	None		Mecklenburg et al. (2011)

79	*Lycodes luetkenii* (Lütken's Eelpout)	849-1436 m	Atlantic-Arctic	None		Mecklenburg et al. (2011)
80	*Lycodes marisalbi* (White Sea eelpout)	91-335 m	Atlantic-Arctic	None		Mecklenburg et al. (2011)
81	*Lycodes mucosus* (saddled eelpout)	5-825 m	Pacific-Arctic	None	Beaufort Sea	Rand & Logerwell (2011), Mecklenburg et al. (2011)
82	*Lycodes paamiuti* (paamiut eelpout)	350-1337 m	Atlantic-Boreal	None		Mecklenburg et al. (2011)
83	*Lycodes pallidus* (pale eelpout)	19-1750	Arctic	None		Mecklenburg et al. (2011)
84	*Lycodes polaris* (Canadian eelpout)	5-300 m	Pacific-Arctic	None	CAO, Beaufort Sea	FiSCAO (2017), Logerwell et al. (2011), Mecklenburg et al. (2011)
85	*Lycodes raridens* (marbled eelpout)	10-400 m	Pacific-Arctic	None	Beaufort Sea	Logerwell et al. (2011), Mecklenburg et al. (2011)
86	*Lycodes reticulatus* (Arctic eelpout)	100-930 m	Atlantic-Arctic	None		Mecklenburg et al. (2011)
87	*Lycodes rossi* (threespot eelpout)	42-365 m	Atlantic-Arctic	None	Beaufort Sea	Rand & Logerwell (2011), Mecklenburg et al. (2011)
88	*Lycodes sagittarius* (archer eelpout)	335-600 m	Arctic	None	CAO	FiSCAO (2017), Mecklenburg et al. (2011)
89	*Lycodes seminudus* (longear eelpout)	357-1400 m	Atlantic-Arctic	None	CAO	FiSCAO (2017), Mecklenburg et al. (2011)
90	*Lycodes squamiventer* (scalebelly eelpout)	357-1808 m	Atlantic-Arctic	None		Mecklenburg et al. (2011)
91	*Lycodes turneri* (polar eelpout)	10-125 m	Atlantic-Arctic	None		Mecklenburg et al. (2011)
92	*Lycodonus flagellicauda*	800-1993 m	Atlantic-Arctic	None		Mecklenburg et al. (2011)
93	*Macrourus berglax*	100-1000 m	Atlantic-Arctic	Commercial	Baffin Bay	Jørgensen et al. (2005)
94	*Mallotus villosus* (capelin)	0-725 m	Boreal-Arctic	Highly commercial	Broad Arctic distribution	Mecklenburg et al. (2011), Rand & Logerwell (2011)
95	*Maulisia microlepis* (smallscale searsid)	500-2000 m	Wide (Atlantic-Indian Ocean)	None	Baffin Bay	Jørgensen et al. (2005)
96	*Melanogrammus aeglefinus* (haddock)	10-450 m	Atlantic-Arctic	Highly commercial	Barents Sea	Olsen et al. (2009)
97	*Myctophum punctatum* (spotted laternfish)	0-1000 m	Atlantic-Boreal	None	Kara Sea	Dolgov (2013)

98	*Myoxocephalus quadricornis* (fourhorn sculpin)	0-100 m	Boreal	No data	Arctic shallow regions	Mecklenburg et al. (2011)
99	*Myoxocephalus scorpioides*	0-275 m	Boreal-Arctic	No data	Arctic shallow regions	Mecklenburg et al. (2011)
100	*Myoxocephalus scorpius*	0-451 m	Temperate-Arctic	Commercial	Circumpolar, slope and shelves	Mecklenburg et al. (2007, 2011)
101	*Nautichthys pribilovius*	0-422 m	Pacific-Arctic	None	Chukchi Sea, Beaufort Sea	Mecklenburg et al. (2011), Rand & Logerwell (2011)
102	*Oncorhynchus gorbuscha*	0-250	Cosmopolitan ?Pacific-subtropical-Boreal	Highly commercial		Andriyashev & Chernova (1996), Mecklenburg et al. (2011, 2018)
103	*Oncorhynchus keta*	0-250 m	Pacific-Boreal	Highly commercial		Andriyashev & Chernova (1996), Mecklenburg et al. (2011, 2018)
104	*Osmerus dentex*	0-290 m	Boreal-Arctic	Commercial	Coastal Arctic of Russia, Alaska and Canada	Mecklenburg et al. (2011)
105	*Osmerus eperlanus*	0-50 m	Atlantic-Boreal	Commercial	White Sea, Barents Sea	Mecklenburg et al. (2011)
106	*Paraliparis bathybius*	20-4009 m	Atlantic-Arctic	None	CAO, Canada Basin, Continental slopes	Stein et al. (2005), Mecklenburg et al. (2011)
107	*Pholis fasciata*	0-94 m	Boreal-Arctic	None	Western Arctic	Mecklenburg et al. (2011)
108	*Platichthys stellatus*	0-375	Pacific-Arctic	Commercial	Bering Sea, Chukchi Sea	Kono et al. (2016)
109	*Pleuronectes quadrituberculatus* (Alaska plaice)	0-600 m	Pacific-Arctic	Commercial	Bering Sea	Andriyashev & Chernova (1996), Mecklenburg et al. (2011, 2018), Yeung & Yang (2014)
110	*Podothecus veternus*	10-605 m	Pacific-Boreal	No data	Bering Sea, Chukchi Sea	Mecklenburg et al. (2011)
111	*Pollachius virens* (saithe)	37-364 m	Atlantic-Arctic	Highly commercial	Barents Sea	Olsen et al. (2009)
112	*Rajella fyllae* (round ray)	170-2050 m	Atlantic-Arctic	None	Baffin Bay, Barents Sea, Greenland Sea, Hudson Bay, Norwegian Sea	Mecklenburg et al. (2011), Lynghammar et al. (2013)
113	*Rajella lintea* (sail ray)	150-1170 m	Atlantic-Boreal	None	Barents Sea, Hudson Sea, Norwegian Sea	Mecklenburg et al. (2011), Lynghammar et al. (2013)
114	*Reinhardtius hippoglossoides* (Greenland halibut)	1-2200 m	Temperate-Arctic	Highly commercial	CAO, Beaufort Sea	FiSCAO (2017), Rand & Logerwell (2011), Mecklenburg et al. (2011)
115	*Rhodichthys regina*	1080-2365 m	Atlantic-Arctic	None	CAO, Canada Basin	Stein et al. (2005), Mecklenburg et al. (2011)

116	*Salvelinus alpinus* (Arctic charr)	0-70 m	Temperate-Arctic	Low commercial interest		Andriyashev & Chernova (1996), Mecklenburg et al. (2011, 2018)
117	*Salvelinus malma* (Dolly varden)	0-200 m	Pacific-Boreal	Commercial	Chukchi Sea, White Sea	Andriyashev & Chernova (1996), Mecklenburg et al. (2011, 2018), Courtney et al. (2016)
118	*Scomber scombrus* (Atlantic mackerel)	0-1000 m	Wide (Atlantic-Mediterranean-Boreal)	Highly commercial	Coast of Jan Mayen	Wienerroither et al. (2011)
119	*Sebastes mentella* (beaked redfish)	300-1441 m	Atlantic-Boreal	Commercial	Barents Sea, Atlantic Arctic	Byrkjedal & Høines (2007), Mecklenburg et al. (2011)
120	*Sebastes norvegicus* (golden redfish)	100-1000 m	Atlantic-Boreal	Highly commercial	Barents Sea, Atlantic Arctic	Byrkjedal & Høines (2007), Mecklenburg et al. (2011)
121	*Somniosus microcephalus* (Greenland shark)	0-2000 m	Atlantic-Arctic	Low commercial interest	Baffin Bay, Barents Sea, Greenland Sea, Greenlnad coast, Hudson Bay, Kara Sea, Norwegian Sea, White Sea	Mecklenburg et al. (2011), Lynghammar et al. (2013)
122	*Squalus acanthias* (picked dogfish)	0-1460 m	Atlantic-Boreal	Commercial	White Sea, Barents Sea, Norwegian Sea, Greenland coast	Mecklenburg et al. (2011), Lynghammar et al. (2013)
123	*Squalus suckleyi* (spotted spiny dogfish)	*15-110 m*	Cosmopolitan ? (Pacific-subtropical)	No data	Bering Sea, Chukchi Sea	Lynghammar et al. (2013)
124	*Stenodus leucichthys*	Coastal	Pacific-Boreal	Low commercial interest		Andriyashev & Chernova (1996), Mecklenburg et al. (2011, 2018)
125	*Stichaeus punctatus*	0-100 m	Boreal-Arctic	None	Bering Sea, Chukchi Sea, Beaufort Sea	Suzuki et al. (2015), Kono et al. (2016)
126	*Stomias boa* (boa scaly dragonfish)	200-2173 m	Wide (Atlantic-Boreal-sub-Antarctic)	None	Baffin Bay	Jørgensen et al. (2005)
127	*Triglops murrayi*	7-530 m	Temperate-Boreal	None	North Atlantic going into the Arctic	Mecklenburg et al. (2011)
128	*Triglops nybelini*	71-1270 m	Atlantic-Arctic	None	Circumpolar	Logerwell et al. (2011), Mecklenburg et al. (2011), Suzuki et al. (2015
129	*Triglops pingelii*	0-930 m	Temperate-Boreal	None	Circumpolar	Logerwell et al. (2011), Mecklenburg et al. (2011)
130	*Zapora silenus* (prowfish)	0-675 m	Pacific-Boreal	None	Bering Sea, Chukchi Sea	Mecklenburg et al. (2011)

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