Drafting a list of important Arctic marine fish species through a multiple perspectives approach bridging ecology, economy, and culture to determine conservation priorities

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Abstract

Arctic marine ecosystems are warming at four times the global average and are shifting to alternate stable states with the increased arrival of sub-Arctic species. A reorganization of trophic dynamics in these systems is likely to modify energy fluxes, impacting the abundance and distribution of many native, migratory, and invasive species. Yet, our basic knowledge of many Arctic marine fishes is underdeveloped. I used a combinatorial framework merging ecological, economic, and cultural knowledge to identify which Arctic marine fish to target for the development of conservation monitoring resources. To develop my multiple perspective list of Arctic marine fish importance, data on trophic ecology, fisheries economics, and Inuit traditional and local knowledge from 25 communities were used. My results show that only half of the identified top 20 most important fishes are endemic to Arctic regions, supporting the widely reported Southernization of Arctic marine ecosystems. I also show that management plans are established for only four species: Greenland halibut (*Reinhardtius hippoglossoides*), Walleye pollock (*Gadus chalcogrammus*), Alaska plaice (*Pleuronectes quadrituberculatus*), and Beaked redfish (*Sebastes mentella*). Other species identified such as Arctic cod (*Boreogadus saida*), Polar cod (*Arctogadus glacialis*), and Shorthorn sculpin (*Myoxocephalus scorpius*), however, are not currently managed despite their demonstrated multifaceted importance. Each list identified species exclusive to that list but also species that were present in other lists, providing both unique and complementary insight into the importance of species. My results highlight the value of bridging multiple perspectives to identify conservation priorities, and underscore the need to collect more fundamental biological data on key marine fishes in the Arctic to better inform conservation/management plans to safeguard Arctic marine biodiversity.

Résumé

Les écosystèmes marins de l'Arctique se réchauffent quatre fois plus vite que la moyenne mondiale et passent à des états stables alternatifs avec l'arrivée accrue d'espèces subarctiques. Une réorganisation des dynamiques trophiques dans ces systèmes est susceptible de modifier les flux d'énergie et d'avoir un impact sur l'abondance et la distribution de nombreuses espèces indigènes, migratrices et envahissantes. Pourtant, nos connaissances de base sur de nombreux poissons marins de l'Arctique sont peu développées. J'ai utilisé un cadre combinatoire fusionnant les connaissances écologiques, économiques et culturelles pour identifier les poissons marins de l'Arctique à cibler pour le développement de ressources de surveillance, ayant comme but la conservation de la biodiversité. Pour dresser ma liste d'importance des poissons marins de l'Arctique, j'ai utilisé des données sur l'écologie trophique, l'économie de la pêche et les connaissances traditionnelles et locales des Inuits provenant de 25 communautés. Mes résultats montrent que seulement la moitié des 20 poissons les plus importants sont endémiques aux régions arctiques, ce qui confirme l'Atlantification/boréalisation des écosystèmes marins de l'Arctique qui est couramment rapportée. Néanmoins, des plans de gestion ne sont établis que pour quatre poissons marins importants de l'Arctique: le flétan noir (*Reinhardtius hippoglossoides*), la goberge de l'Alaska (*Gadus chalcogrammus*), la plie d'Alaska (*Pleuronectes quadrituberculatus*) et le sébaste du Nord (*Sebastes mentella*). Cependant, les populations de morue arctique (*Boreogadus saida*), de morue polaire (*Arctogadus glacialis*) et de Chaboisseau à épines courtes (*Myoxocephalus scorpius*) ne sont pas actuellement gérées, en dépit de leur importance multiforme avérée. Chaque type de connaissance a apporté des renseignements uniques ainsi que complémentaires sur l'importance des poissons marins de l'Arctique, car chaque liste identifie des espèces communes et des espèces uniques entre les listes. Mes résultats

mettent en évidence la valeur de l'intégration de perspectives multiples pour identifier les priorités en matière de conservation et soulignent la nécessité de collecter davantage de données biologiques fondamentales sur les principaux poissons marins de l'Arctique afin de mieux informer les plans de conservation/gestion pour sauvegarder la biodiversité marine de l'Arctique.

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Contribution of authors

I wrote Chapters 1, 2, 4, and 5. For the manuscript included in this thesis (Chapter 3), I contributed conceptualization, methodology, software, validation, formal analysis, investigation, data curation, writing – original draft, and visualization. Dr. Roy contributed to the manuscript in the form of conceptualization, methodology, formal analysis, resources, supervision, writing – review & editing, visualization, project administration, and funding acquisition. Dr. Hussey contributed to the manuscript in the form of conceptualization, validation, and writing – review & editing.

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List of abbreviations

AIC – Akaike Information Criterion

BIC – Bayesian Information Criterion

CAO – central Arctic Ocean

CAFF – Conservation of Arctic Flora and Fauna

COSEWIC – Committee on the Status of Endangered Wildlife in Canada

DFO – Department of Fisheries and Oceans Canada

FAO – Food and Agriculture Organization of the United Nations

IPCC – Intergovernmental Panel on Climate Change

ICES – International Council for the Exploration of the Sea

IUCN – International Union for Conservation of Nature

IQ – Inuit Qaujimajatuqangit

MEY – Maximum economic yield

NOEP – National Ocean Economics Program

NAFO – Northwest Atlantic Fisheries Organization

NPFMC – North Pacific Fishery Management Council

NCRI – Nunavut Coastal Resource Inventory

PERMANOVA – Permutational multivariate analysis of variance

PCA – Principal components analysis

TEK – Traditional ecological knowledge

Chapter 1: Introduction

Marine ecosystems worldwide, from coasts to the deep sea, are under threat due to increasing human impact (Glover and Smith, 2003; Crain et al., 2009). The main anthropogenic stressors driving this impact are pollution, over-fishing, benthic habitat destruction, natural resource extraction, and climate change (Glover and Smith, 2003). However, the scope and impact of these stressors vary widely in time and space (Halpern et al., 2007). Concurrent impacts can also cause additive, antagonistic, or synergistic effects on marine ecosystems (Crain et al., 2008), leading to further uncertainty regarding the timing and direction of future ecological shifts. Arctic marine ecosystems are among the most impacted, warming at a rate up to four times the global average due to complex feedback processes (Holland and Bitz, 2003; Hoegh-Guldberg and Bruno, 2010; IPCC 2019, Rantanen et al. 2022). Consequently, sea and air temperatures are rising, and sea ice thickness and extent are being continually reduced (Box et al., 2019; Bush and Lemmen, 2019). These ecosystem-wide changes may shift trophic links in local food webs, permanently restructuring them (e.g., Huntington et al., 2020).

Indeed, studies report the invasion of many non-native boreal species into these warming Arctic ecosystems, including the Atlantic cod (*Gadus morha*) and haddock (*Melanogrammus aeglefinus*), often coinciding with decreases in native piscivorous species such as the Greenland halibut (*Reinhardtius hippoglossoides*; Wassman et al., 2011; Renaud et al., 2012; Fossheim et al., 2015; Frainer et al., 2017; Andrews et al., 2019). Capelin (*Mallotus villosus*) have also increased in abundance at higher latitudes, correlating with a shift in Arctic Char (*Salvelinus alpinus*) diet (Ulrich and Tallman, 2021) and potential declines in Arctic cod (*Boreogadus saida*) abundance and biomass (Florko et al., 2021). This warming phenomenon and the community changes that ensue are being termed the "borealization/Atlantification/Southernization" of the Arctic Ocean (Fossheim et al., 2015; Goldsmit et al. 2018; Chan et al. 2019; Polyakov et al., 2020; Levine et al. 2023). Changes in trophic dynamics are likely to affect community composition and energy flux in these ecosystems which many native and migratory species, as well as Indigenous communities, depend on for survival and cultural expression. More recent concerns in the Artic involve increasing ocean acidification, oxygen depletion, and human exploitation of newly ice-free zones (Stortini et al., 2016; Terhaar et al., 2020; Fauchald et al., 2021).

Additionally, our understanding of the physiology, ecology, and population dynamics of most endemic Arctic marine fish species remains limited (Van Pelt et al. 2017; Coad and Reist 2018; Snoeijs-Leijonmalm et al. 2020). Since the loss of endemic fish species in the Arctic due to the continued environmental changes seems inevitable (Niittynen et al. 2018; Frainier et al. 2021; Layton et al. 2021), there is an urgent need to prioritize species for conservation, especially given limited resources and time. Indeed, only around ~25% of Arctic marine fish have been assessed by the International Union for Conservation of Nature (IUCN 2023).

Climate change has also negatively affected Inuit culture and food security through changes in Arctic food web structure (Ford 2009; Beaumier et al. 2015; Desjardins 2020). The loss of sea ice threatens food security through wildlife population declines and subsequent harvest restrictions that lead to increases in cost for locally harvested food (Kenny and Chan, 2016), which is essential for both cultural expression and nutrition.

Given the significant current and projected disturbances to Arctic ecosystems, my thesis attempts to identify the most important Arctic marine fish species while considering ecological, economic, and cultural perspectives. Various hurdles in studying Arctic marine ecosystems (logistical, financial, climatic, etc.) are important factors contributing to data scarcity about endemic species. However, another barrier in establishing an inclusive list of species importance has been the disconnect between the perspectives of western science, economic entities (e.g., fisheries, wildlife management agencies), and traditional ecological knowledge (TEK), each having their own respective values and priorities. While an increasing number of researchers are tackling scientific challenges in the Arctic with interdisciplinary approaches due to their advantages (Falardeau and Bennett 2019; Kutz and Tomaselli 2019; Wheeler et al. 2020; Lauter 2023), there has not been a formal attempt to integrate species conservation priorities across ecology, economy, and culture, in part due to the oft-conflicting priorities of economic, scientific and community interests. Thus, in an effort to integrate these different perspectives, my project will compile a list of important species for each of the three perspectives. The lists will be merged to produce an integrative importance list which will be used to guide the development of basic knowledge of the most crucial, understudied Arctic marine fish species.

The main objective of my research is to compile and combine lists of important Arctic marine fish species through an ecological, economic, and cultural perspective to establish which species to prioritize for conservation. I hypothesize that each perspective will provide a complementary set of species (i.e., species unique to a single perspective as well as species identified by other perspectives) due to differences in priorities, values, and the evidence available. I predict that by combining these importance lists even in a simple way, I can provide an interdisciplinary perspective on Arctic marine fish importance to determine conservation needs as a starting point for further research and data collection.

1.1 Thesis format

This thesis will be presented in a manuscript format, with Chapter 1 containing the general introduction, Chapter 2 containing a comprehensive review of the literature, Chapter 3 containing the manuscript submitted for publication in *Biological Conservation*, Chapter 4 containing the synthesis, and Chapter 5 containing the conclusion. The supplementary material for the manuscript is provided as a supplementary document to the thesis due to document length constraints.

Chapter 2: Comprehensive review of the literature

In the following comprehensive review, I will synthesize the literature's current, recorded recognition of the importance of marine fish species present in the Arctic through ecological, economic, and cultural perspectives. I will gather all available information on strictly marine species, although any lack of information on these will be compensated by information on anadromous species, with a marine habitat focus. For example, most culturally important fishes are reliant on freshwater to some extent and thus that review will discuss anadromous species. In my submitted manuscript (Chapter 3), the focus is shifted to strictly marine species to identify important fishes that marine conservation policy and monitoring can target year-round. Each important species' current conservation context will also be described, namely in the context of a general lack of data about Arctic endemic marine fish (Van Pelt et al. 2017; Snoeijs-Leijonmalm et al. 2020) and of a need for priorities in conservation planning due to limited resources.

2.1 Known ecologically important marine fish of the Arctic

Arctic cod have long been recognized as a crucial, keystone species in Arctic food webs due to their circumpolar distribution and high abundance. They depend on sea ice for spawning and egg development, and are well adapted for cold temperatures, having lipid-rich muscle and the ability to produce anti-freeze glycoproteins (Chen et al. 1997). As consumers of copepods and amphipods and prey for a large variety of fish, seabirds, and marine mammals, they represent most of the energy flux between algae consumers and piscivores in Arctic marine ecosystems (Welch et al. 1992; Loseto et al. 2009; Darnis et al. 2012; Hop and Gjøsæter 2013; Kuletz et al. 2015; Stevenson et al. 2019). While they are currently classified as Least Concern by the International Union for Conservation of Nature's (IUCN) Red List of Threatened Species, their population trends remain unknown (IUCN 2023). Thus, there exist some concerns about their future due to their dependence on sea ice and Southernization putting their population at risk of significant habitat loss due to a warming Arctic (Florko et al. 2021; McNicholl et al. 2021; Falardeau et al. 2022; Geoffroy et al. 2023). Their population structure also remains unclear due to conflicting results from multiple independent studies (Gordeeva and Mishin 2019; Wilson et al. 2019; Nelson et al. 2020; Maes et al. 2021), slowing genomic investigation progress.

Arctic staghorn sculpin are demersal fish (*Gymnocanthus tricuspis*) that inhabit Arctic, Subarctic, and adjacent Atlantic and Pacific waters. They are a common species in certain parts of their large range (Allen and Smith 1988; Mecklenburg et al. 2018). Due to their high abundance, they are an important element of Arctic trophic webs (Livingston et al. 2017; Gray et al. 2017; Tokranov et al. 2022), serving as prey for piscivorous fish, seabirds, and marine mammals (Finley and Evans 1983; Atkinson and Percy 1991, 1992; Elliott et al. 2008; Walkusz et al., 2012; Gray et al., 2017). Thus, they represent an important link between benthic invertebrates and higher trophic levels. They are also considered an indicator of Arctic marine ecosystem health (Mecklenburg et al., 2007). The IUCN lists them as Least Concern, but as with previous species, their population trends are unknown.

Shorthorn sculpin are mid-trophic level cottids that are common in the western Arctic (Barber et al. 1997; Norcross et al. 2013). They are known to be important trophic links, being both predators and prey in the Chukchi, Baltic, Beaufort, and Bering seas as well as the high Arctic (Atkinson and Percy 1992; Smith et al. 1997; Cardinale 2000; Cui et al. 2012; Rand et al. 2013; Whitehouse et al. 2017; Gray et al., 2017; Landry et al. 2018). Similarly to Arctic staghorn sculpin, their generalist feeding behaviour and abundance potentially make this an appropriate sentinel species of Arctic trophic dynamics. However, their range and movement are being significantly altered by anthropogenic disturbances in Arctic waters, namely increasing vessel traffic (Ivanova et al. 2018; Landry et al. 2019).

Arctic char are important, widespread, anadromous predators in Arctic marine, coastal, and freshwater habitats. Although not strictly marine, they are a very important Arctic food web component. They spawn in lakes and migrate to the sea in the summer, serving as an important linkage between ecozones. Summer feeding on abundant, energy-rich prey is crucial to increase their body condition and lipid stores before the winter (Dutil 1986). In fact, char feed almost exclusively on invertebrates and forage fish (sand lance, capelin, herring, cod, and sculpin are the most common) in the marine environment (Spares et al. 2012; Bengtsson et al. 2023) and feeding during overwintering in lakes is very rare (Dutil 1986; Swanson et al. 2011). Char can also be used as a sentinel species for monitoring climate change in the Arctic because their health reflects changes in Arctic food webs as their anadromous life cycle relies on different habitats and prey, rendering it susceptible to multiple environmental pressures (Power et al., 2012; Coad and Reist 2018; Falardeau et al. 2022; Carlström 2023). Looking towards the future, climate change is affecting char in seemingly contradictory ways. Falardeau et al. (2022) found that both Inuit knowledge keepers and biophysical indicators indicated that longer ice-free seasons may have a positive effect on fish condition and lipid content. However, the northward expansion of Atlantic and Pacific species combined with increasing ocean and lake temperatures are predicted to significantly reduce Arctic char’s range (Chu et al. 2005; Reist et al. 2006; Hein et al. 2012). Despite these imminent threats, the species is listed as “Least Concern” on the IUCN Red List even though its population trends are reportedly unknown (IUCN 2023).

As expected, the species known to be important are widely distributed and abundant, rendering their study more logistically feasible than rarely occurring species with small home ranges, in terms of space and/or depth. Interestingly, all the species discussed have life histories that are specifically adapted for Arctic ecosystems, suggesting they might be especially vulnerable to accelerated environmental shifts due to the contraction of their already restricted range. This thesis will attempt to systematically dredge the primary and secondary literature for as much quantitative diet information on Arctic piscivorous predators as possible. The goal is to obtain a comprehensive, quantitative understanding of Arctic trophic dynamics to determine the most important prey species which sustain those food webs.

2.2 Known economically important marine fish of the Arctic

Atlantic cod populations are the basis of historically and, to a lesser extent, presently important fisheries in the Northwest Atlantic Ocean (Rose 2007; Hutchings and Rangeley 2011). The Canadian population managed by the Northwest Atlantic Fisheries Organization (NAFO) was indeed once the largest in the world (Hutchings and Myers 1994) and catches reflected this, with over 800 000 metric tons fished in that region (Brattey et al. 2009). They remain one of the most important commercial species in the North Atlantic despite significant declines that started in the 1990s due to population collapse (Brattey et al. 2009; Hutchings and Rangeley 2011). European populations in the North Sea and off the Icelandic shelf also saw steep declines around this time as warming sea temperatures and overfishing exerted simultaneous pressure on Atlantic cod populations (O’Brien et al. 2000; Astthorsson et al. 2002). In addition, projections predict that these populations are expected to decline even further by 2100, with Atlantic cod instead expanding their range northwards into sub-Arctic and Arctic seas (Drinkwater 2005). Their inability to recover from these collapses has been related to fishing mortality, changes to life history (namely reductions in age and size at maturity), and increased natural mortality (Hutchings and Rangeley 2011). Atlantic cod's response to climate change is generally agreed to be overall negative, as they are listed as "Vulnerable" on the IUCN Red List with unpecified population trends, although the species was last assessed in 1996 (IUCN 2023). However, it remains unclear exactly how northern populations will react to the rapidly changing environmental conditions, as changes in Arctic primary production, trophic dynamics, and industrial fishing also remain uncertain. A common conclusion from predictions about negative climate change effects is range reduction (Perry et al. 2005; Reist et al. 2006). The recovery of these fisheries could take decades, but the feat remains possible through a combined approach utilizing strengthened legislation, integrated management strategies, sustainable seafood certification practices, expansion of marine protected areas, and financial incentives for sustainable fisheries investments (Hu and Wroblewski 2009; Hutchings and Rangeley 2011; Hernandez et al. 2013; Sinclair-Waters et al. 2018).

Greenland halibut is a commercially important flatfish supporting demersal fisheries in northern regions of both the Atlantic and Pacific Oceans (Smidt 1969; Godø and Haug 1989; Bowering and Brodie 1995), with some recorded observations along the continental slope of the Arctic Ocean (Majewski et al. 2017; Mecklenburg et al. 2018; Orlova et al. 2019; Orlov et al. 2021). Nevertheless, a suitable habitat model for the species predicts a pan-Arctic distribution (Vihtakari et al. 2021), further emphasizing its economic potential as sea ice is reduced and novel fisheries are established in Arctic waters. As an existing example, the offshore Greenland halibut fishery in the Davis Strait, west Greenland, continues to be productive and the stock stable in spite of its historical exploitation (Jacobsen et al. 2018). This fishery even earned the Marine Stewardship Council certification recently (Cappell et al., 2017; Cook et al., 2019), although this decision was met with criticism (Long and Jones 2021). The halibut fishery is crucial to the economy of Greenland; the Greenlandic fishing industry accounts for up to 95% of the country's export income (The Economic Council 2017; Jacobsen 2018), with halibut contributing approximately 30% of the total income (The Economic Council 2017). However, recent studies warn of possible overexploitation of this stock using more robust modelling methods (Fredenslund 2022; Jensen et al. 2024). Although annual stock assessments are made by NAFO using survey data, a recent study used a towed benthic video sled to demonstrate extensive physical evidence of trawling on the benthic environment, raising concerns about the sustainability of deep-sea fisheries (Long et al. 2021). In Canada, Greenland halibut also has a 2023 Conservation Harvesting Plan (DFO 2023), and its northern populations are co-managed with Inuit communities in Canada (DFO 2019). In Europe, fishing quotas are negotiated between Greenland, the Faroe Islands, and Norway (Howell et al. 2023).

In the following paragraphs, I will discuss the marine fisheries of certain anadromous species in sub-Arctic zones due to the lack of information on other strictly marine species of commercial interest.

Arctic char is among the most important species that Canadian fisheries harvest in the Arctic, mainly in the regions of Cambridge Bay and Pangnirtung (Zeller et al. 2011; Lemire et al. 2015; Coad and Reist 2018). Char are also harvested in northern Sweden, albeit to a significantly lesser extent (Gren et al. 2023). Anadromous populations, which spawn in lakes are migrate to the ocean in the summer to feed, are preferred for commercial purposes due to a generally bigger size and a higher quality flesh because of additional nutrients obtained from consuming marine prey (Evans et al. 2015; Lemire et al. 2015). The largest commercial Arctic Char fishery in Canada located in Cambridge Bay (Harris et al. 2021) was valued at 4 100 000 dollars for the 2008 to 2012 period (DFO 2014), and is co-managed by local, regional, territorial, and federal stakeholders. Given the immense economic benefits that Arctic Char fisheries provide to Inuit communities, the demand for Char is high and exceeds the current supply (Galappaththi et al. 2022), which highlights the large potential for the establishment of additional fisheries in the Canadian Arctic. Since small-scale catches are a very important facet of Arctic char commercialization, the importance of subsistence economy to many Arctic communities cannot be understated; the financial health of some communities depends almost solely on the economic viability of their fisheries.

Whitefish (*Coregonus* spp.) are anadromous salmonids that were widely harvested across the Arctic. They are mostly fished by Russia, which had large fisheries in the Kara Sea and maintains fisheries in the Laptev and East Siberian Seas. Zeller et al. (2011) reconstructed catches in Arctic marine environments, as the official numbers were too low to be reflective of the actual productivity and use of Arctic fisheries. These fisheries mainly target least cisco (*C. sardinella*), Arctic cisco (*C. automnalis*), and broad whitefish (*C. nasus*). In the Kara Sea, they estimated a catch of 6 200 tons/year of least cisco in 1950, which declined to 50 tons/year in 2006. In the Laptev Sea, the estimated catch remained mostly constant due to a lack of initial data and indicated 1 100 tons/year for least cisco and up to 800 tons/year for Arctic cisco. In the

East Siberian Sea, they estimated the least cisco catch at 800 tons/year in 1950, growing to 1 600 tons/year in 2006; similarly, catches of broad whitefish were estimated at 200 tons/year in 1950 and doubled by 2004; in contrast, landings of Arctic cisco decreased from 350 tons/year in 1950 to 260 tons/year in 2006. While seemingly insignificant amounts compared to catches in Atlantic and Pacific seas, these harvests often represent a significant percentage of the income for the northern communities in which these fisheries are based (Zeller et al. 2011). Thus, it is worrying that abiotic shifts driven by climate change might significantly affect harvests because whitefish are keystone components of Arctic ecosystems linking freshwater, estuarine, and marine environments through their migrations (Coad and Reist 2018). In terms of conservation status, the IUCN Red List has not assessed Arctic cisco. Least cisco and broad whitefish are labeled as "Least Concern", yet once again their population trends are unknown (IUCN 2023).

Atlantic salmon (*Salmo salar*) are anadromous salmonids exploited in commercial, subsistence and recreational fisheries across the Atlantic Ocean (COSEWIC 2010; Hindar et al. 2011). The main causes of their importance are a unique life cycle, immense popularity as a sport fish, commercial importance, and close proximity to large population centers (Noakes 2014). In Norway and Finland, they are also harvested for subsistence and commercial purposes (Brattland and Mustonen 2018). Net pen salmon farming is an important sector of the global seafood industry, made evident by the more than 1 400 000 tons of Atlantic salmon raised annually (Noakes 2014). The conservation context of the species highlights the vulnerability of this species to climate change. The total abundance of Atlantic salmon has declined during the last three decades, both in terms of number of populations and reduced productivity in freshwater and the marine environment (Hindar et al. 2011; Chaput 2012; ICES 2016). This decline is hypothesized to have been significantly influenced by anthropogenic factors such as dam construction, habitat alterations or destruction, disease, water contamination, overexploitation, parasites, and climate change (Parrish et al. 1998). Recent and past evidence also suggests they may also be shifting their marine distribution northward due to climate change causing warming sea surface temperatures (Todd et al. 2011; Chittenden et al. 2013; Bilous and Dunmall 2020). The main threat to their populations is currently escaped farmed fish due to genetic introgression, but salmon lice parasites were identified as an expanding threat (Forseth et al. 2017). To protect their populations, management of several anthropogenic threats, namely unsustainable exploitation, must be prioritized (Forseth et al. 2013). The IUCN Red List assessment reflects these conditions since they are labeled as "Near Threatened" with an overall decreasing population trend (IUCN 2023).

Pacific salmon (*Oncorhynchus* spp.) are a genus of commercially important anadromous salmonids (Dunmall et al. 2013; Noakes 2014; Dunmall et al. 2018). Chum (*O. keta*) and pink (*O. gorbuscha*) salmon have a relatively small but documented presence in the Arctic and are the only species of Pacific salmon with native populations in the Arctic (Irvine et al. 2009; Nielsen et al. 2013). Chinook salmon (*O. tshawytscha*), sockeye salmon (*O. nerka*), and coho salmon (*O. kisutch*) are seemingly rare in Arctic waters and have probably not yet established populations at those latitudes (Nielson et al. 2013). As opposed to their congeners, chum and pink salmon spend very little time in freshwater and migrate to the ocean soon after they hatch and are used extensively in salmon enhancement hatcheries throughout the North Pacific (Noakes 2014). Ocean ranched pink and chum salmon are the most widely harvested Pacific salmon in that region and thus contribute substantially to commercial fisheries (Noakes 2014). In the Chukchi

Sea, chum salmon catches were estimated at around 1 300 tons/year in 1950, peaked at approximately 3 500 tons/year in 1980, and sat at 1 500 tons/year in 2006 (Zeller et al. 2011). Chum and pink salmon are currently unassessed by the IUCN Red List.

An important note is that very little catches are officially reported to the Food and Agriculture Organization of the United Nations (FAO) in the Arctic Ocean (FAO statistical area 18; Zeller et al. 2011). Indeed, reconstructed catches are estimated to be approximately 950 000 metric tons between 1950 and 2006 instead of the officially reported figure of 12 700 tons (Zeller et al. 2011), showcasing the regular circumvention of official fishery reports by vessels in the Arctic from Russia, the United States, and Canada. This thesis will attempt to partially address this lack of data by relying on reconstructed catches from a repository ideally informed by international, national, regional, and local landings reports. The Sea Around Us database (seaaroundus.org; Pauly et al. 2020) is a prime candidate as a data source due to its comprehensiveness and accessibility. Regardless, I will make an effort to find other data sources that could compliment or replace Sea Around Us since that database is only based on international and national reports as baselines for the interpolation of catch time series, and excludes any local/regional reports.

2.3 Known culturally important marine fish of the Arctic

Greenland halibut is the most important commercial fish stock for residents of Greenland, with more than hundreds of fishermen applying for official licenses in Upernavik (and dozens that fish without a license; Delaney et al. 2012). The subsistence harvest of halibut is crucial to locals for its role in the mixed economy of the region. Fishing provides the spending power necessary for work materials work such as bullets, nets, or snowmobiles, as well as for housing, transport, food, and recreation (Delaney et al. 2012). For example, well over one third of working age men in the Upernavik region officially sell Greenland Halibut as part of their self-employment income in 2010 (Delaney et al. 2012). Halibut also supports the important local cultural practices like “kødgaver” which translates to “gifting of meat”, a practice that remains both culturally and nutritionally important in smaller, remote communities (Delaney et al. 2012). However, the government of Greenland proposed changes to the management of halibut in 2011, including the closing the Upernavik fishery to new entrants in 2012, raising concerns about where locals will work if they can not earn an income from fishing (Delaney et al. 2012). In Canada, the main Arctic fishery is co-managed (DFO 2019) and is located off the east coast of Baffin Island, where catches peaked at 18 000 tons in 1992, stabilized at around 10 000 tons until 2000, and finally increased to 24 155 tons in 2007 (Coad and Reist 2018).

In the following paragraphs, I will discuss the cultural importance of certain anadromous species to Indigenous communities in the Arctic since they see the most traditional use compared to marine species.

Arctic char are harvested as a subsistence fish throughout Nunavut as well as in Nunavik and the Northwest Territories, east of the Mackenzie River (Riedlinger and Berkes 2001; Usher 2002; Nichols et al. 2004; McBeath and Shepro 2007; Kuhnlein and Receveur 2007; Barber et al. 2008; Pearce et al. 2009; Zeller et al. 2011; Coad and Reist 2018; McNicholl et al. 2020), although they’ve been fished by Indigenous Peoples for thousands of years (Friesen 2002, 2004). As a natural resource, they are cornerstones of culture, food security, and human health for Inuit, a disproportionately vulnerable demographic in terms of food insecurity. They are currently co-managed in most of the Canadian Arctic by a mix of government, territorial and local organizations, as well as diverse stakeholders (DFO 2014). In Nunavut, the total food replacement value of Arctic Char subsistence fisheries was estimated at 7 200 000 dollars a year in 2016 (Government of Nunavut 2016).

Whitefish (Arctic cisco, least cisco, and broad whitefish) are culturally important to various Indigenous Peoples around the world. Indeed, subsistence fisheries operate in Yakutia in northern Russia, at the coast and inland tributaries of the Laptev and East Siberian Seas (Popova et al. 2020) as well as in the Chukchi Sea (Zeller et al. 2011). Some smaller subsistence fishing also occurs at the coast of the Kara Sea by Nenet communities (Davydov and Mikhailova 2011). In North America, they support the substantive subsistence fisheries of western Arctic Indigenous communities in Canada and Alaska (Kuhnlein and Receveur 2007; McBeath and Shepro 2007; ABR Inc. et al. 2007; George et al. 2009; Coad and Reist 2018; Carothers et al. 2019; McNicholl et al. 2020). Harvests have been traditionally large to meet consumption needs of both humans and sled dogs; cisco represent a high percentage of the local diet of some communities (e.g., Nuiqsut in Alaska), and are sold, bartered, or gifted to family and friends within the community because they are often an important source of protein (ABR Inc. et al. 2007; George et al. 2009; Cotton 2012). Since they accumulate fat during their anadromous migration, they are reportedly quite tasty when smoked (Coad and Reist 2018). However, fishers of a northern Alaska community started reporting evidence of disease in the Arctic cisco they caught in the late 2000s. Observations included belly spots, sickly livers, discolored flesh, and irregular protrusions, although an important factor of this condition decline could be the close proximity of the community to oil and gas exploitation facilities (McBeath and Shepro 2007).

Regardless, the harvest in northern Alaksa seemed to remain sustainable as an independent report found that harvest rates of Arctic cisco from 1987 to 2007 in Nuiqsut did not negatively impact new recruitment to the western Beaufort Sea (ABR Inc. et al. 2007).

Pacific (mostly chum and pink) salmon are harvested by subsistence fishers in various Indigenous communities of northern Alaska and the western Canadian Arctic (Kuhnlein and Receveur 2007; Cotton 2012; Noakes 2014; Fall et al. 2017; Carothers et al. 2019). In fact, both scientific studies and local and Indigenous knowledge report that catches and use of Pacific salmon have been increasing in these regions since the 1990s, as salmon expand their range northwards (McBeath and Shepro 2007; Fechhelm et al. 2009; Moss et al. 2009; Cotton 2012; Dunmall et al. 2013; Brown et al. 2016; Carothers et al. 2019; Chila et al. 2022). Most salmon caught by Utqiaġvik residents are harvested in the Elson Lagoon fishery (Brewster et al. 2008; George et al. 2009; Cotton 2012). In 2011, chum (42% of catch) and pink salmon (23% of catch) made up the majority of the recorded summer Elson Lagoon catch (Cotton, 2012). Additionally, in some Alaskan fisheries, Chinook salmon (*O. tshawytscha*) have been increasingly targeted, but catches are generally low (Cotton 2012). In Nuiqsut and the Northwest Territores, however, salmon have historically represented a very small portion of the subsistence fish catch (Fechhelm et al. 2009; McNicholl et al. 2020). Evidently, salmon have been progressively becoming integral to the food security, cultural practices, health, and local economy of various Indigenous communities in northern Alaska and the western Canadian Arctic over time (Carothers et al. 2019; Steel 2020; Atlas et al. 2021; Chila et al. 2022).

Atlantic salmon are traditionally fished by the Skolt Sámi in northern Europe, although in small quantities (Brattland and Mustonen 2018; Mustonen et al. 2018). The salmon fishery in the Neiden/Näätämö River at the border of Norway and Finland can be dated back to the 1740s. Due to dwindling salmon returns and increasing concern for the wild salmon, the drift net fishery at sea was abandoned in 1989, and the coastal and river fisheries have been reduced by shortening the allowable fishing period and limiting permitted fishing gear (Brattland and Mustonen 2018). The large cuts to quotas for the traditional fishery have increasingly led to protests from local Sámi fishers, politicians, researchers, communities, and the Sámi Parliaments in Norway and Finland (Brattland and Mustonen 2018). Their main concern is that the Norwegian government does not recognize any specific Sámi right to fish as a priority group in fishery regulations unlike some First Nations (e.g., Inuit) in Canada. However, the Sámi contest that salmon fisheries are an integral part of their traditional way of life and thus there exists an Indigenous right to fish (Brattland and Mustonen 2018). It was these concerns and disagreements that led the Sámi to design and lead the Näätämö River Co-Management Project in 2011. However, the lack of recognition by the state officials of this type of co-management remains an ongoing challenge for local communities.

The previously described case studies highlight the importance of these fishes to Northern communities worldwide, which goes far beyond mere subsistence. Indigenous fisheries provide food and financial security to over 40 ethnic groups in the Arctic (Fondahl et al. 2015). They are critical to communities' health, economic stability, and cultural identity (Kuhnlein and Receveur 1996; Proverbs et al. 2020; Chila et al. 2022). Indeed, fishing is an important part of Indigenous ways of life, helping to "strengthen community networks, facilitate the transmission of knowledge, and preserve cultural traditions" (Wight et al. 2023; see also Thorsteinson and Love 2016; Loring et al. 2019; Proverbs et al. 2020; Galappaththi et al. 2022). Nonetheless, recent environmental shifts are forcing Arctic residents to adapt to rapidly changing conditions to maintain their livelihood and lifestyle. The predicted socio-cultural consequences for coastal communities due to climate change include cultural heritage loss (via species extirpation), health disparities and worsening food and water security (via dwindling populations/condition of regularly consumed species; Fritz et al. 2017; Stephen 2018; Irrgang et al. 2019; Alvarez et al. 2020).

While there have been individual community reports about which fish species are culturally important to those communities, there is no single consensus about which to prioritize for conservation except for Arctic char in Canada due to its immense cultural, economic, and nutritional importance across the Inuit Nunangat. To address this, I would ideally need the time, contacts, and resources (logistical, financial, and human) to conduct a circumpolar survey of various Indigenous Arctic Peoples (Athabaskan, Inuit, Gwich'in, Dolgan, Sámi, etc.) in several countries (Canada, Greenland, Finland, Norway, Russia, Sweden, and the United States) to responsibly design the study, collect the data, select the analyses, and interpret the results to determine which fish species share importance among Peoples the most. Unfortunately, with limited time, contacts, and resources, I only have access to Indigenous secondary literature, which is an emerging field as Indigenous communities, organizations, and governments acquire technological expertise and equipment. One such example is the Nunavut Coastal Resource Inventories, a rare repository of Indigenous local and traditional knowledge on occurrences of marine mammals, fish, and seabirds. These documents, prepared by a mix of academics and local experts from over twenty communities across Nunavut, contain information on coastal resources and activities obtained from community interviews, research, reports, maps, and other resources. These inventories are a means of gathering reliable information on coastal resources to facilitate their strategic assessment, economic development, coastal management, and conservation opportunities. Moreover, the documents represent the preservation of traditional knowledge (Inuit Qaujimajatuqangit) through written codification, historically rare for Indigenous Peoples with oral traditions such as the Inuit, and the preparation for future environmental changes. I will use the occurrence reports of marine species to estimate individual species occurrence across communities and to quantify each species' contribution to community dissimilarity using multivariate techniques (e.g., PCA).

2.4 Bridging text

Since ecological, economical, and cultural perspectives are likely to prioritize fish importance differently, incorporating these three perspectives to derive a combined importance list for species conservation and management would seem appropriate. Such an integrated priority species list would better reflect the different epistemologies of the varied perspectives to generate a more inclusive list that would maximize the use of limited conservation resources. Combining different types of knowledge to address wildlife conservation recognizes the interdependencies between society and the environment. It can also identify new insights about multifaceted issues, and lead to the development of actionable strategies better representing the interests of all stakeholders (Alexander et al. 2019; Falardeau et al. 2022; Drake et al. 2023). There is a growing interest in bridging various knowledge systems to better assess socio-ecological challenges (Falardeau and Bennett 2019; Wheeler et al. 2020; Lauter 2023). This stems from federal legal requirements (*Impact Assessment Act*, 2019; *Canadian Environmental Protection Act*, 1999; *Oceans Act*, 1996; see Cooke et al. 2016) and international commitments (e.g., Intergovernmental Panel on Climate Change, United Nations Declaration on the Rights of Indigenous Peoples, Arctic Council, International Agreement to Prevent Unregulated High Seas Fisheries in the Central Arctic Ocean) to include Indigenous Traditional and Local Knowledge systems (e.g., Inuit Qaujimajatuqangi) into conservation strategies and policies. It also recognizes the historical exclusion of TEK from formal decision-making processes in the past, and the increasing research capacity of Indigenous communities (e.g., Nunavut Arctic College, Nunavut Research Institute; Inuit Tapitiit Kanatami 2018). In the context of Arctic marine fish species, drawing on diverse knowledge systems also expands the available information on otherwise data deficient species, increasing the legitimacy of conclusions drawn, and building trust between Indigenous Knowledge keepers and Western scientists (Alexander et al. 2019; Falardeau et al. 2022; Patterson et al. 2023).

Chapter 3: Bridging science, economy, and culture to identify priority Arctic marine fish species for the development of conservation monitoring resources

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3.1 Abstract

Arctic marine ecosystems are warming at four times the global average and are shifting to alternate stable states with the increased arrival of sub-Arctic species. A reorganization of trophic dynamics in these systems is likely to modify energy fluxes, impacting the abundance and distribution of many native, migratory, and invasive species. Yet, our basic knowledge of many Arctic marine fishes is underdeveloped. We used a combinatorial framework merging ecological, economic, and cultural knowledge to identify which Arctic marine fish to target for the development of conservation monitoring resources. To develop our multiple perspective list of Arctic marine fish importance, data on trophic ecology, fisheries economics, and Inuit traditional and local knowledge from 25 communities were used. Our results show that only half of the identified top 20 most important fishes are endemic to Arctic regions, supporting the widely reported Southernization of Arctic marine ecosystems. We also show that management plans are established for only four species: Greenland halibut (*Reinhardtius hippoglossoides*), Walleye pollock (*Gadus chalcogrammus*), Alaska plaice (*Pleuronectes quadrituberculatus*), and Beaked

redfish (*Sebastes mentella*). Other species identified such as Arctic cod (*Boreogadus saida*), Polar cod (*Arctogadus glacialis*), and Shorthorn sculpin (*Myoxocephalus scorpius*), however are not currently managed despite their demonstrated multifaceted importance. Each list identified species exclusive to that list but also species that were present in other lists, providing both unique and complementary insight into the importance of species. Our results highlight the value of bridging multiple perspectives to identify conservation priorities, and underscores the need to collect more fundamental biological data on key marine fishes in the Arctic to better inform conservation/management plans to safeguard Arctic marine biodiversity.

Keywords: Arctic marine ecosystems, Arctic marine fishes, Arctic marine biodiversity, trophic interactions, catch forecasting, Inuit traditional knowledge, bridging knowledge.

3.2 Introduction

Arctic marine ecosystems are among the most impacted by climate change, warming at four times the global average (IPCC 2019; Rantanen et al. 2022). Consequently, air and sea temperatures are rising, and sea ice thickness and extent have decreased over the last 40 years (Box et al. 2019; Bush and Lemmen 2019; IPCC 2022). Such ecosystem-wide changes are altering trophic links in Arctic food webs, shifting them to an alternate stable state (Yurkowski et al. 2018; Huntington et al. 2020; Ulrich and Tallman 2021). The mostly small-sized and benthic fishes inhabiting the Arctic are slowly being encroached upon by larger, pelagic fishes, and community functional diversity is therefore increasing (Frainier et al. 2017; 2021). This reorganization is likely to modify community composition and energy flux (Kortsch et al. 2015; Stevenson et al. 2019), affecting the abundance and distribution of many native, migratory, and invasive species. Recent reports also describe rising oxygen depletion, and human exploitation in newly ice-free zones at increasingly higher latitudes (Meredith et al. 2019; Fauchald et al. 2021). As species, fisheries, shipping lanes, and natural resource extraction move further north, the combined pressures of climate change and human-induced stressors will inevitably change Arctic marine ecosystems further.

Over the last two decades, studies have reported the encroachment of historically Atlantic and Pacific fishes into warming Arctic marine waters, and an increasing trend of northward expanding species overall (von Biela et al. 2023; Levine et al. 2023; Nielsen et al. in press). These northward-shifting species are likely to compete with native species, especially when their diets substantially overlap, as is the case for capelin and Arctic cod (McNicholl et al. 2016). While some Arctic fishes have been studied in some detail due to their ecological, economic, and/or cultural importance (e.g., Arctic cod, *Boreogadus saida*; Greenland halibut, *Reinhardtius hippoglossoides*), our understanding of the physiology, ecology, and population dynamics of the more than 1,400 other Arctic marine fishes remains limited (Van Pelt et al. 2017; Coad and Reist 2018; Snoeijs-Leijonmalm et al. 2020). Since the loss of endemic fishes in the Arctic seems inevitable in light of continued environmental change (Frainier et al. 2021; Layton et al. 2021), there is a need to prioritize species for conservation monitoring, especially given the limited resources and time available.

Some fishes are undeniably central to the sustained function of Arctic marine ecosystems, but the importance of a species can be considered from ecological, economic, and cultural perspectives, among others (Noble et al. 2016; Coe and Gaoue 2020). Since each perspective is likely to identify different fishes, incorporating them together to derive a combined importance list for species conservation and management would seem logical. Such an integrated species list would better reflect the different epistemologies of the varied perspectives to generate a more inclusive list. Recent efforts to bridge knowledge types illustrate that these methods maximize the benefits of limited conservation resources, help identify long-term patterns of environmental change, and lead to the development of actionable strategies better representing the interests of all stakeholders (Alexander et al. 2019; Falardeau et al. 2022; Drake et al. 2023). In the context of Arctic marine fish species, drawing on diverse knowledge systems also expands the available information on otherwise data deficient species, increasing the legitimacy of conclusions drawn, and building trust between Indigenous Knowledge keepers and Western scientists (Alexander et al. 2019; Falardeau et al. 2022; Patterson et al. 2023).

Here, we present a strategy to build a list of Arctic marine fishes which can then be used to prioritize them for conservation and management. This was done by gathering data through ecological, economic, and cultural perspectives to determine species importance. We use diet information from Arctic piscivores, forecasted prospects from 2015-2034 of landed weight and monetary value data from reports on fisheries catches in Arctic and sub-Arctic waters, and occurrence reports from 25 Nunavut Coastal Resource Inventories (NCRIs), a repository of Inuit Qaujimajatuqangi (IQ), to generate three perspective-specific fish species importance lists. We then combine these lists into one, identifying and prioritizing marine fishes for conservation in the Arctic, based on combined perspectives. We hypothesize that each perspective will provide a list of species exclusive to that perspective and species present in other perspectives, thus providing both unique and complementary insight into the importance of Arctic marine fishes.

We predict that by combining the lists derived from these perspectives, we can provide a multidisciplinary view on priority needs for Arctic marine fish conservation. We also assess the conservation status of each identified species using the International Union for Conservation of Nature's Red List (IUCN 2023) as a representation of the conservation attention each species has received to date to further prioritize management efforts.

3.3 Methods

3.3.1 Ecological importance

From the literature, we compiled a list of strictly Arctic marine piscivores (i.e., that live and breed north of the Arctic circle; CAFF 2013) including marine mammals, seabirds, and fish. In total, we investigated the diet of 20 marine mammals from nine families (Odobenidae, Phocidae, Balaenidae, Balaenopteridae, Eschrichtiidae, Delphinidae, Monodontidae, Phocoenidae, and Ziphiidae), 22 seabirds from six families (Gaviidae, Procellariidae, Phalacrocoracidae, Stercorariidae, Laridae, and Alcidae), and 53 fishes from nine families (Rajidae, Gadidae, Cottidae, Agonidae, Psychrolutidae, Cyclopteridae, Liparidae, Zoarcidae, and Pleuronectidae). Although most marine mammals and seabirds are identifiable and phylogenetically defined, new marine fishes are routinely discovered in Arctic waters, especially in bathypelagic and abyssopelagic zones (Mecklenburg et al. 2011; Coad and Reist 2018). Thus, we excluded piscivore species on the CAFF list that only had a holotype or fewer than five type specimens.

We gathered peer-reviewed literature on the diet of identified Arctic marine piscivores using systematic review techniques (Moher et al. 2009). We developed a modifiable search string and selection criteria, searching for relevant articles published between January 1st, 1970, and

January 1st, 2023 using Scopus (Table S1; Figure S1). We limited our search back to 1970 due to an effort to standardize stomach content analysis methods around that time (Hyslop 1980; Pierce and Boyle 1991). We did not consider strictly presence/absence diet data, stable isotope, or DNA metabarcoding diet inference because these techniques do not provide quantifiable proportions of species-specific diet items necessary to our analyses (Ahlbeck et al. 2012; Nielsen et al. 2018; Kuhrt et al. 2023). After removing duplicate studies, we screened titles and abstracts of remaining articles, and retained only those adhering to defined inclusion criteria (Table S1; Figure S1). Additional potential sources from the reference list of used studies were also screened to a time limit of 1970. We then scanned the full texts of retained articles to determine study eligibility (i.e., fish in diets identified to at least family level). All available data on piscivorous species, prey types, frequency of occurrence, and biomass proportion (as defined in da Silveira et al. 2020) were extracted from selected articles. All statistical analyses were performed using R version 4.3.0 (R Core Development Team 2023).

We filtered the dataset for strictly marine prey supported by five sources or more, ensuring enough replicate studies were available to provide adequate statistical power in our reported ecological data. We quantified the dietary importance of prey species using two ecological indices; (i) mean frequency of occurrence ($\overline{FO}$; i.e., how often a species is found in a predator's stomach) and (ii) mean biomass proportion ($\overline{B}$; i.e., the proportion of mass or volume of a species in a predator's stomach relative to other contents; Cui et al. 2012). To determine species importance, we z-score normalized our two indices and averaged them to obtain an integrated score for each listed fish. We also fit a broken stick regression model with breakpoints assessed by Bayesian Information Criteria, to identify significant shifts in the relationship between $\overline{FO}$

and $\overline{B}$ using the *segmented* package in R (Muggeo 2008). To avoid overfitting the data but still capture the best number of possible breakpoints, we set the maximum number of breaks to *Kmax* = 5. We also repeated the broken-stick analysis but included only Arctic endemics (i.e., species whose major distributions and whose life histories play out above the Arctic circle; CAFF 2013) in the model. Because our ecological list was the shortest of the derived perspective lists (see section 3.1), it was used as a base to compare with the others.

3.3.2 Economic importance

We obtained aggregated reconstructed fisheries landings (in weight) and monetary value of landed catches data for 199 species from commercial and subsistence fisheries operating in Arctic and sub-Arctic zones of the United Nations Food and Agriculture Organization (FAO zones 18, 21, 27, 61, and 67). This included the Exclusive Economic Zones of Canada, the United States (Alaska), Iceland, Denmark (Greenland and the Faroe Islands), Norway (including Jan Mayen and Svalbard Islands), and Russia. These data were compiled by the National Ocean Economics Program (NOEP) for the years 1950–2014. The NOEP database reflects data reconstructed by the Sea Around Us project (https://www.seaaroundus.org/), but also includes data from the FAO and various regional and international fisheries landings reports. Because available data for the years 2015 onwards do not include such regional and international reports, we did not use these data for our economic assessments. Instead, we used time series modelling of historic aggregated landings and values (between 1950-2014), to project how these are expected to change in the 20 years following (2015-2034) and used (i) their forecasted mean weight landed ($\overline{WL}$) and (ii) mean value sold ($\overline{VS}$; price in USD at 2005 value) as economic importance indices. As with the ecological data, and to provide confidence in our estimates, we excluded 26 species with less than five years of historical data. We also excluded 8 species with mean historic landings and values of 0, which would result in forecasted zeros landings and values. Due to our focus on strictly marine species, we removed another 35 species that were anadromous, catadromous, and amphidromous fishes. Time series based predictions were performed using the forecast package in R (Hyndman and Khandakar 2008). The *auto.arima* function was used to automatically fit the best autoregressive integrated moving average (ARIMA) model to the landings and values time series of 130 species. This automated function uses a variation of the Hyndman-Khandakar algorithm, combining unit root tests with minimization of the corrected Akaike Information Criterion (AIC) and maximum likelihood estimation to assess time series model fit while accounting for temporal autocorrelation in the data (Kwiatkowski et al. 1992; Hyndman and Khandakar 2008; Hyndman and Athanasopoulos 2018). The forecasting analyses also provided bootstrapped 95% confidence intervals for estimates using 10,000 iterations. As with the ecological data, we normalized and averaged the indices into one integrated score per species and ranked them. Broken stick regressions were fit to the $\overline{WL}$ vs. $\overline{VS}$ values as with the ecological data (again using $Kmax = 5$), to identify significant breakpoints in the relationship. Broken stick models were run on all species, and just for Arctic endemic fishes.

3.3.3 Cultural importance

The Government of Nunavut's ministry of Transportation and Economic Development – Fisheries and Sealing Division provides a collection of Nunavut coastal resource inventories (NCRIs) for 25 coastal communities spread throughout Nunavut's territory. These inventories catalogue information acquired through community interviews, hunting and fishing activities, and research reports, listing the sightings, use, and location of living resources in those communities (https://gov.nu.ca/environment/information/nunavut-coastal-resource-inventory). Throughout a decade of noticeable climate changes, many Inuit communities across Nunavut collected Traditional and Local Knowledge (Inuit Qaujimajatuqangit, IQ) on their activities and resource use to inform the management, development, and conservation of coastal resources. NCRIs were initiated as an effort by the Igloolik community in 2007, codifying Local and Traditional Knowledge in a more permanent and retrievable format, atypical of IQ. To our knowledge, no comparable published databases with quantified observational counts are available for individual marine fish species in other northern territories and countries. Thus, data from NCRIs reflect the sightings of wildlife species by more than 190 community members involved in the collection and use of natural resources, termed knowledge holders (Inuit Circumpolar Council Alaska 2016). We used marine fish observations reported in NCRIs to assess fish species' cultural importance for the 25 listed communities. From these repositories of IQ, we consulted over 4,200 observations of marine fish species. Each observation details a geo-referenced encounter with a marine fish species resulting from either subsistence activities (i.e., fishing) or coincidental sighting. We identified 86 unique species enumerated across the 25 NCRIs. Forty-nine species were excluded from our analysis due to rarity (observed in < 5 communities), as were 12 anadromous species.

As each observation in the NCRIs represents the inherent connection between a knowledgeable and representative community member and a marine resource, we used (i) the mean number of observations across communities ($\overline{OC}$) as our first index of importance. To clarify differences in reported community composition, we used a site by species matrix populated with observational counts to run a Principal Components Analysis (PCA) based on the unscaled community-level dissimilarity matrix (Table S2). The initial dissimilarity matrix was Hellinger transformed to account for high zeros typical of count based data (Oksanen et al. 2022), prior to running the PCA. Species scores along constructed PC axes 1 and 2 were extracted and used to generate our second index of importance as (ii) the square root of the summed squared magnitudes of each species' contribution to the PC axes (i.e., $\overrightarrow{PCA_i} = \sqrt{PCA1_i^2 + PCA2_i^2}$). As such, species with vectors of larger magnitude contribute more to differences in marine fish community composition than others. Cultural importance scores were calculated by averaging the two normalized cultural indices as in previous analyses. Finally, we fit a broken stick regression to the $\overline{OC}$ vs. $\overrightarrow{PCA}$ dataset to identify significant breakpoints (with *Kmax* = 5), both using the overall data and focusing only on Arctic endemics.

3.3.4 Combined list

To combine our three perspectives, we summed the normalized importance scores across all lists. Using scores normalized to the number of individuals in each list ensures an equitable consideration of every species across all lists. This resulted in the most important species having the highest integrated scores. To put the final list results into the context of current international and Canadian conservation designations, we assessed each species' status based on the International Union for Conservation of Nature's Red List of Threatened Species (IUCN 2023) and the Committee on the Status of Endangered Wildlife in Canada (COSEWIC), respectively.

3.4 Results

3.4.1 Ecological importance

Our systematic review on Arctic predator diets resulted in an initial gathering of 2,610 articles from the peer-reviewed literature. After the elimination of duplicates, abstract/summary screening, and final selection, we retained 84 articles for data extraction, most of which provided information on marine mammal and seabird piscivores. Only four articles contained data about piscivorous fish diets (Table S3; Figure S1). From these articles, we extracted more than 1,200 observations of 107 different fish prey categories in predator diets, although only 20 prey were supported by five or more studies (Figure 1).

To determine the importance of each fish to the diet of Arctic predators, we summarized mean frequency of occurrence ($\overline{FO}$) and biomass proportion ($\overline{B}$), and their standard errors. We found a large variety of fishes in Arctic piscivore diets, ranging from small forage fish to larger semi-pelagic species (Table S4; Figure 1a). The most prevalent and consumed prey were Arctic cod, Capelin (*Mallotus villosus*), Atlantic herring (*Clupea harengus*), Walleye pollock (*Gadus chalcogrammus*), and Polar cod (*Arctogadus glacialis*). These species scored higher along both indices, and consequently in normalized pooled importance, than other prey fish (Table S4; Figure 1a). Saffron cod (*Eleginus gracilis*) was the only outlier, found frequently in piscivore stomachs but in small quantities (Figure 1a). When considering all prey species, the broken-stick model showed a significant relationship between the two indices ($\overline{B}$ = 0.70 ± 0.16 $\overline{FO}$ - 2.97 ± 3.59, and $\overline{B}$ = 3.18 ± 2.09 $\overline{FO}$ - 99.24, adj. R^2 = 0.67, df = 16, p < 0.001; Figure 1a) and estimated one significant breakpoint at $\overline{FO}$ = 38.68% ± 4.12, and $\overline{B}$ = 24.11 ± 8.31 (BIC_0 = 149.47, BIC_1 = 147.14, BIC_2 = 160.49, BIC_3 = 161.49, BIC_4 = 162.49, BIC_5 = 163.49). This indicated that above this threshold, prey items took on greater importance in piscivore diets. Filtering the list to include only the 8 endemic Arctic prey species, the broken stick converged on a model without breakpoints between $\overline{FO}$ and $\overline{B}$. Nevertheless, the linear model was significant ($\overline{B}$ = 0.75 ± 0.24 $\overline{FO}$ - 4.33 ± 7.08, adj. R^2 = 0.52, *df* = 7, $p < 0.05$), but with reduced explanatory power. While the endemic Arctic prey species relationship was smoother, it did not impact the relative importance of the remaining prey species. This likely indicates that invasive sub-Arctic prey species drive the apparent breakpoint in our overall species assessment. In particular, sand lance, Golden redfish (*Sebastes norvegicus*), Pacific herring (*Clupea pallasii*), Pollock (*Pollachius pollachius*), Atlantic cod (*Gadus morhua*), Haddock (*Melanogrammus aeglefinus*), and Blue whiting (*Micromesistius poutassou*) constituted the initial, flatter part of the relationship, while Capelin amplified the importance past the breakpoint. The list of normalized scores ranking fishes based on the ecological perspective is presented in Table S4 and indices for all taxa in Table S5.

3.4.2 Economic importance

Time series forecasts based on the historical NOEP compiled data of weights landed ($\overline{WL}$) and the values sold ($\overline{VS}$) for each individual species were used to successfully predict their economic importance over the period 2015-2034 (see DRYAD link). The broken stick model gauging the economic importance of all 130 species showed a significant relationship between indices ($\overline{VS}$ = $1.54 \times 10^3 \pm 1.64 \times 10^2$ $\overline{WL}$ - $4.61 \times 10^6 \pm 1.79 \times 10^7$, and $\overline{VS}$ = $-1.92 \times 10^3 \pm 1.35 \times 10^3$ $\overline{WL}$ + 4.13×10^9, adj. R^2 = 0.58, *df* = 126, $p < 0.001$; Figure 2a) and estimated one significant breakpoint at $\overline{WL}$ = $1.19 \times 10^6 \pm 1.18 \times 10^5$ metric tons, and $\overline{VS}$ = $1.84 \times 10^9 \pm 2.21 \times 10^7$ USD (BIC_0 = 5,399.65, BIC_1 = 5,394.76, BIC_2 = 5,395.76, BIC_3 = 5,396.75, BIC_4 = 5,397.76, BIC_5 = 5,398.76). We found that both established (historically important; e.g., Atlantic cod) and expanding (whose catches are increasing; e.g., Blue whiting) fisheries in the North Atlantic and North Pacific are expected to dominate economic importance in the Arctic over the next decade. Gadids and small forage fish were predicted to be the most harvested and sold species across the circumpolar Arctic and sub-Arctic (Table S6; Figure 2a). Atlantic cod remained the most profitable species despite the collapse of major fisheries in the early 1990s (Figure 2a; Figure S2a,b; Hutchings and Myers 1994; Myers et al. 1997). Walleye pollock was likely to become a substantially more important fishery in terms of $\overline{WL}$, increasing by over 50% compared to its pre-2015 average, however its value sold was expected to remain low (Figure 2a; Figure S2c,d). Atlantic herring, Blue whiting, Haddock, Pacific cod (*Gadus macrocephalus*), Saithe (*Pollachius virens*), Atlantic mackerel (*Scomber scombrus*), Capelin, and Greenland halibut scored higher in importance relative to most other species (Table S6; Figure 2a), with the remaining species clustered near the origin.

When considering only the 13 Arctic endemic species, the broken stick model identified a single significant breakpoint between indices at $\overline{WL}$ = 1.06 x 10^5 ± 3.41 x 10^4 metric tons and $\overline{VS}$ = 3.67 x 10^8 ± 6.29 x 10^7 USD (BIC_0 = 525.06, BIC_1 = 506.81, BIC_2 = 507.81, BIC_3 = 508.81, BIC_4 = 509.81, BIC_5 = 510.81; Figure 2b). This breakpoint was largely driven by the Walleye pollock outlier, indicating that after this threshold, fisheries tended to return less value per landed ton than expected. The overall relationship between economic indices for endemic Arctic species was significant ($\overline{VS}$ = 3.63 x 10^3 ± 1.11 x 10^3 $\overline{WL}$ - 1.80 x 10^7 ± 1.83 x 10^7, and $\overline{VS}$ = 65.80 ± 51.08 $\overline{WL}$ + 3.60 x 10^8, *adj.* R^2 = 0.90, *df* = 9, $p < 0.001$; Figure 2b). Walleye pollock was likely to dominate future economic importance of Arctic marine fishes, with average traded values predicted to remain stable at around 400 million USD. Greenland halibut, a traditionally exploited Arctic marine fish, was expected to increase in importance with traded values increasing by close to 300% pre-2015 averages, to almost 450 million USD. Less well-known species such as Beaked redfish (*Sebastes mentella*) were also expected to remain economically important, but most other species clustered near the origin with low $\overline{WL}$ and $\overline{VS}$ values (Figure 2b). The economic importance list composed of normalized scores is presented in Table S6 and indices for all taxa in Table S7.

3.4.3 Cultural importance

Of the 86 unique species listed in the 25 NCRIs, we determined the number of observations per species within each community for 25 fishes that were observed in 5 or more communities (see section 2.3). From this, we determined the relative abundance of each species in each community (Figure S3a). Arctic cod, Shorthorn sculpin (*Myoxocephalus scorpius*), Greenland shark (*Somniosus microcephalus*), Capelin, and Greenland halibut were among the most commonly reported fish by Inuit knowledge keepers across Nunavut (Figure S3a). Arctic cod was found in all but one community, Baker Lake, where Shorthorn sculpin dominated instead. Generally, NCRIs showed diverse fish assemblages in most communities with very few dominated by just one or two species (save Baker Lake), and no obvious trend with latitude (Figure S3a).

The PCA performed on the raw number of observations per species per community accounted for just over 40% of the variation in fish assemblages observed among communities (Figure S3b). While no geographical pattern in the species assemblages among communities was obvious, species separated communities along PC axes. Arctic cod, Arctic staghorn sculpin (*Gymnocanthus tricuspis*), Arctic eelpout (*Lycodes reticulatus*), Capelin, and Winter flounder (*Pseudopleuronectes americanus*) separated Igloolik, Kugluktuk, Chesterfield Inlet, Arctic Bay, Kimmirut, Gjoa Haven, and Resolute Bay from the remaining communities, which scored positively along PCA1. Similarly, Greenland shark, Shorthorn sculpin, Greenland halibut, Arctic skate (*Amblyraja hyperborea*), and Northern hagfish (*Myxine glutinosa*) separated the communities of Baker Lake, Grise Fjord, Resolute Bay, Clyde River, Arctic Bay, Pond Inlet, Cape Dorset, Kugaaruk, and Igloolik from the rest, which scored positively along PCA2. Generally, most species contributed to both axes but with varying magnitudes and directions. Among those with the largest magnitudes were Greenland shark, Shorthorn sculpin, Arctic cod, Capelin, Lumpsucker (*Cyclopterus lumpus*), Arctic staghorn sculpin, and Greenland cod (*Gadus ogac*; Figure S3b).

The broken stick model for our cultural indices identified a single significant breakpoint in the overall data at $\overline{OC}$ = 8.47 ± 1.21, and $\overrightarrow{PCA}$ = 0.40 ± 0.09 (BIC_0 = -57.40, BIC_1 = -57.52, BIC_2 = -56.52, BIC_3 = -55.52, BIC_4 = -54.52, BIC_5 = -53.52). This was primarily driven by Greenland halibut, which had more than 10 observations in Pangnirtung, Pond Inlet, and Grise Fiord, but very low occurrence everywhere else, and Arctic cod which was common to most communities but with a lower than expected $\overrightarrow{PCA}$ magnitude. The broken-stick model showed a significant relationship between cultural indices ($\overrightarrow{PCA}$ = 0.05 ± 0.01 $\overline{OC}$ - 0.02 ± 0.03, and $\overrightarrow{PCA}$ = -0.0011 ± 0.02 $\overline{OC}$ + 0.39, *adj.* R^2 = 0.80, df = 21, p < 0.001; Figure 3a) with a smooth and increasing relationship until the breakpoint. Species that largely differentiated the communities (as seen in Figure S3b) scored highly on both indices; namely, Arctic cod, Shorthorn sculpin, Greenland shark, Lumpsucker, Capelin, Greenland cod, Arctic staghorn sculpin, Polar cod, and Atlantic cod. The remaining species had an $\overline{OC}$ less than five and a species $\overrightarrow{PCA}$ of less than 0.25 (Figure 3a). When considering only the 17 Arctic endemic species, the broken-stick model failed to identify any breakpoints in the relationship. Nevertheless, the linear model was significant ($\overrightarrow{PCA}$ = 0.04 ± 0.01 $\overline{OC}$ + 0.01 ±

0.03, *adj.* $R^2 = 0.77$, $df = 15$, $p < 0.001$). The most important cultural species among Arctic endemic fishes were found in the top right corner of the relationship, and included Arctic cod, Shorthorn sculpin, Greenland shark, Greenland halibut, Greenland cod, Arctic staghorn sculpin, and Polar cod (Figure 3b). The cultural importance list composed of normalized scores is presented in Table S8 and indices for all taxa in Table S9.

3.4.4 Combined list

Overall, our ecological, economic, and cultural importance lists returned 20, 130, and 25 species, respectively. We summed the normalized importance scores across all lists to obtain an integrated score over all perspectives (Table 1). We identified a total of 148 unique species occurring in at least one of the three lists. By using scores normalized to the number of species in each list, the final list weighed all perspectives equally, providing an equitable estimate of the importance of Arctic marine fishes, given the data used. However, of the top 20 species listed, only half were endemic to the Arctic with the remainder originating from more southern seas. Most of the top 20 species were observed on multiple lists, indicating their importance under more than one perspective. Six species were jointly identified across all three lists, 13 species by the ecological and economic lists, 12 species by the ecological and cultural lists, and seven species by the economic and cultural lists.

Of the total of 148 species in our combined list, the conservation status of 29 (~20%) have not yet been assessed by the IUCN and 129 (87~%) by COSEWIC. Of those that have been assessed by the IUCN, three (~2%) are listed as critically endangered, five (3%) as endangered, 13 (~9%) as vulnerable, 10 (~7%) as near threatened, 80 (~54%) as least concern, and six (~4%) as data deficient (Table 1). In terms of population trends, 51 species (~34%) had unknown trends, three (~2%) had unspecified trends (i.e., unstable trends), 33 (~22%) had negative trends, 20 (~14%) had stable trends, and 12 (~8%) had positive trends (Table 1). Of those that have been assessed by COSEWIC, 5 (~3%) are endangered, 5 (~3%) are threatened, 3 (~2%) are under special concern, two (~1%) are data deficient, and four (~3%) are not at risk.

3.5 Discussion

Here, we used a basic combinatorial framework encompassing ecological, economic, and cultural knowledge to identify the most important Arctic marine fishes to subsequently prioritize future research and conservation efforts based on their current management context. We found that only 27 of the 148 identified species are endemic to Arctic seas and management plans are established for only four Arctic species: Greenland halibut, Walleye pollock, Alaska plaice (*Pleuronectes quadrituberculatus*), and Beaked redfish. Conversely, other important species identified such as Arctic cod, Polar cod, and Shorthorn sculpin are not currently managed (at least not in Canada). Each perspective provided unique and complementary insights into the importance of Arctic marine fishes, since each list highlights species present in other lists, but also some that were exclusive to that perspective. These results further show that embracing different perspectives provides a more inclusive approach to identify a greater variety of species than would have been possible using only one. To some extent, each perspective list also supported the ongoing Southernization of Arctic marine ecosystems, with many species from the Atlantic and Pacific included as important. This work represents an initial attempt at bridging varied perspectives to establish the importance of Arctic marine fishes, through assimilating quantifiable data but still maintaining statistical standards in performed analyses. The final derived list highlights that, while many important Arctic fishes have received research attention (e.g., Atlantic cod, Walleye pollock, Greenland shark), and others are being increasingly studied (e.g., Greenland halibut, Arctic cod), the vast majority of fishes present in the Arctic remain understudied relative to their importance (e.g., Arctic staghorn sculpin, Polar cod, Shorthorn sculpin, Saffron cod). While only a small number are officially listed as data deficient, many are listed as least concern but this is based on minimal data (IUCN 2023). Our generated list of Arctic marine fish species allows an assessment of species importance while considering their current conservation context to ultimately help prioritize those requiring the development of conservation and management resources.

3.5.1 Ecological importance

This list demonstrated that Arctic cod, Capelin, Atlantic herring, Walleye pollock, and Polar cod are key Arctic marine prey species, whose mean occurrence and biomass proportions are above and beyond that of other species in the diet of predators. These results are consistent with previous studies outlining the importance of these species, especially Arctic cod which has been identified as central to Arctic marine ecosystems (Darnis et al. 2012; Stevenson et al. 2019; Geoffroy et al. 2023). Surprisingly, the ecological list contained the lowest number of species (20) of the three generated lists, which is counterintuitive considering the extensive amount of literature we assessed for inclusion into the systematic review. This might be because few of the predators surveyed are generalist piscivores consuming instead only a few prey that are common and highly abundant, as seen on this list. This matches previous expectations for simplified food webs and trophic interactions in Arctic ecosystems (Darnis et al. 2012). Most predators surveyed were also pelagic, benthic, and/or demersal and occurred in coastal regions (CAFF 2013), limiting our understanding of prey importance in deeper habitats (e.g., bathypelagic, abyssopelagic) where other species may be important (e.g., angler and lantern fishes). We only included four articles on piscivorous fish diets because these were the only ones containing quantitative data identifying prey to at least family levels in the Arctic. This potentially overlooks many fish-fish interactions that would involve, and increase the importance of, other fish species.

Our ecological list was based on diet information available in the scientific peer-reviewed literature and therefore provides a proxy for trophic interactions. As a result, it does not account for marine fish species that may be ecologically important in some other capacity within the Arctic ecosystem, such as ecosystem engineers. Trophic interactions are nevertheless crucial to ecosystem functioning and are highly impacted by climate change in the Arctic (Andrews et al. 2019; Falardeau et al. 2022). Consequently, we believe our focus on trophic interactions provides an important perspective on ecological importance. It is also important to note that there are limited data available on the ecological roles of Arctic marine fishes outside of trophic interactions. As devised, the relevance of our ecological list is also apparent given many species topping this list rank highly in the economic and cultural lists, underscoring their multifaceted importance (e.g., Arctic Cod, Walleye pollock, Atlantic herring). The ecological list also identifies species using a perspective that is most decoupled from human use (relative to economic and cultural perspectives) and therefore includes species that would either be absent or have low ranks in other lists.

The ecological list demonstrated the ongoing Southernization of Arctic marine waters. The fact that Capelin, Sand lance, Atlantic herring, and Atlantic cod are included, and considered by many to be sub-Arctic invaders, supports the notion that sub-Arctic species are increasingly integrated in Arctic marine food webs (Goldsmit et al. 2018; Pedro et al. 2020; Florko et al. 2021). Although

Arctic cod and Capelin have a similar energetic value and nutritional composition (Pedro et al. 2019; Brisson-Curadeau and Elliott 2019), many marine sea bird and seal diets have shifted away from Arctic cod and towards other available prey fish (Choy et al. 2017; Lowther et al. 2017), with negative consequences for their breeding success and fitness (Florko et al. 2021; Falardeau et al. 2022; Geoffroy et al. 2023). Our results also support the importance of Walleye pollock as key prey for Arctic predators (Smith 1981; Springer 1992), although there are concerns of increasing competition with Pacific herring, another sub-Arctic invader (Sturdevant et al. 2001). When sub-Arctic invaders were removed from the ecological analysis, the breakpoint observed in the relationship using all species disappeared. This suggests that sub-Arctic fishes may be driving an important shift in overall species importance after the established threshold through their integration into Arctic marine food webs (Goldsmit et al. 2018; Pedro et al. 2020; Florko et al. 2021).

Nevertheless, and despite large-scale anticipated Arctic marine ecosystem changes (IPCC 2019; Rantanen et al. 2022), established conservation plans do not exist for many of the species identified on the ecological list. For example, there is no established conservation plan for Arctic cod despite its dependence on diminishing sea ice and increased competition from sub-Arctic invaders (Pettitt-Wade et al. 2021; Falardeau et al. 2022; Geoffroy et al. 2023). Similarly, conservation plans for Polar cod, an ice associated species considered important to the functioning of Arctic marine ecosystems and widely consumed by many predators (see section 3.1; Pettitt-Wade et al. 2021) are non-existent. Very little is known about the population structure or population trends of Polar cod (Pettitt-Wade et al. 2021), and it has yet to be assessed by the IUCN Red List. The conservation status of Saffron cod, also found in predator diets, has not been assessed (IUCN 2023).

Consequently, our ecological list identifies several marine fishes crucial to the trophic dynamics in the Arctic and that should likely be prioritized for conservation.

3.5.2 Economic importance

The economic perspective list illustrates the potential of Atlantic cod, Walleye pollock, Atlantic herring, Blue whiting, Haddock, Saithe, Pacific cod, Atlantic mackerel, and Capelin to become the most important fisheries in the Arctic because their predicted average landed weight and value sold will be substantially higher than those of other evaluated species. Our results are consistent with other reports predicting the growing importance of Atlantic cod, Greenland halibut, Capelin, and Beaked redfish fisheries in Arctic waters (Tai et al. 2019; Steiner et al. 2024). Our economic relationships identified breakpoints indicating a threshold at which the weight landed no longer generated the expected value sold. This could be indicative of fisheries operating beyond their maximum economic yields (MEY), whereby excess landed fish flood markets and become less valuable as a commodity (Dichmont et al. 2010; Diop et al. 2018). Specifically, Walleye pollock, and European plaice appear important at tempering these relationships. Because these relationships are based on predicted values, they suggest that these fisheries may operate beyond their MEY, and thus become unsustainable in the future. The inclusion of the economic perspective list adds complementarity to the combined perspectives list by identifying many fishes shared with both the ecological and cultural lists. However, the focus of the economic perspective on commercial trade results in ranking most species relatively low (i.e., ecologically important species that are not commercially exploited). The fact that most high-ranking species on the economics lists were not ranked on the other two lists, however, underscores how the economic perspective adds unique insight to our assessment. This is particularly important since this perspective is tightly coupled with human use, as humans use fish resources as food globally (FAO 2024).

The economic list identified the highest number of sub-Arctic species, which is expected given the NOEP data used were taken from both Arctic and sub-Arctic zones as delimited by the FAO. While this likely overpopulated the overall list, it was necessary to capture as many fisheries operating above the Arctic circle but below the High Arctic Ocean (where a moratorium is currently in place). For example, if we had restricted our dataset to only include the Arctic Sea FAO zone (18), we would likely have missed emerging fisheries in the Arctic (e.g., Greenland halibut in Baffin Bay, Northwest Greenland, and the Beaufort Sea, Blue whiting, Beaked redfish and Atlantic cod in Baffin Bay and the Northeast Arctic; Tai et al. 2019; ICES 2020). The challenge of including only fisheries operating North of the Arctic circle but below the High Arctic demonstrates the need to better delineate Arctic marine regions for fisheries management, as is the case for the North Atlantic with the Northwest Atlantic Fishing Organization (NAFO) and the International Committee for the Exploration of the Sea (ICES) delimited regions. This is especially important considering increasingly open and accessible Arctic seas.

While most economically important Arctic fishes are well-studied, knowledge gaps remain for certain species projected to become important in the future. Overall, few Arctic marine species targeted by fisheries have had their conservation status evaluated by the IUCN (Christiansen et al. 2014). When considering current conservation context, Greenland halibut has a recent Conservation Harvesting Plan (DFO 2023a), and its northern populations are co-managed with Inuit communities in Canada (Hussey et al. 2017; DFO 2019). Fishing quotas for Greenland halibut are also negotiated between Greenland, the Faroe Islands, and Norway (Howell et al. 2023). Walleye pollock fisheries in the Eastern Bering Sea are managed by the United States' North Pacific Fishery Management Council (NPFMC 2015) and those in the Western Bering Sea and the Sea of Okhotsk by the Russian Federation's Federal Fisheries Agency. However, Beaked redfish fisheries are currently being evaluated for sustainable use by DFO in the Northwest Atlantic (DFO 2023b) and by ICES in the Northeast Arctic (ICES 2020). A predicted 20-fold increase in fisheries potential in the Arctic will lead to some species becoming the basis for important fisheries in coming decades (Van Pelt et al. 2017; Tai et al. 2019). Consequently, formalising a list of species that should be prioritized for future conservation and management, as presented here, will be valuable for avoiding overexploitation (Ye and Gutierrez 2017; Nilsson et al. 2019).

3.5.3 Cultural importance

The cultural list contributes broadly to our understanding of Arctic marine fish importance through the inclusion of Inuit traditional knowledge. The relationship considering all species showed a steady increase in prevalence of species with increasing ability to distinguish northern coastal fish communities to a breakpoint, after which the relationship flattened. This flattening indicates that species scoring after the breakpoint are less useful than expected in determining the structure of northern coastal communities. Species scoring beyond the breakpoint included Arctic cod, Shorthorn sculpin, Greenland shark, and to some extent, Greenland halibut. This result is expected considering these latter species are prevalent in most communities and while still observed often and at many locations, have limited distinguishing power due to their extensive ranges. The high prevalence of these species is consistent with existing reports documenting their widespread occurrence across the circumpolar Arctic, not just the Canadian Arctic (Nielsen et al. 2014; Brand

and Fischer 2016; Landry et al. 2018; Devine et al. 2018; Deary et al. 2021). The cultural lists also demonstrate the importance of species not ranked as highly (or at all) in the other two lists. Specifically, Shorthorn sculpin, Greenland shark, and Greenland cod, were ranked higher, illustrating that incorporating this perspective into our analyses broadened the scope of what is typically considered an important species for conservation purposes. The Greenland shark, for example, while not commercially important, is a major bycatch issue in northern fisheries and is considered a challenging species for conservation given its life history traits (Edwards et al. 2019).

It is important to note that fish species observed among communities were identified and recognized by community members and natural resource users (NCRIs). This exemplifies the inherent knowledge of Inuit of these species in those areas with an understanding that these species are present in the proximity of those communities. Often this knowledge is not translated or made available to more traditional science given it is usually orally transmitted between community members (Riedlinger and Berkes 2001). Moreover, to be identified/recognised, a species must also have an inherent value (for good or bad) to those recognising it, and it is this value that our cultural indices attempt to, at least partially, reflect.

The cultural list further provides evidence for the ongoing Southernization of Arctic marine waters. The breakpoint observed in the overall relationship was not strong (i.e., difference from $BIC_0 < 1$) and was largely influenced by the presence of Capelin and Atlantic cod, and to a lesser extent, Lumpsucker, Northern hagfish, and Sand lance, all sub-Arctic species. When sub-Arctic species were excluded from the analyses, the breakpoint disappeared, and the relationship was weaker, but more predictable. To us this demonstrates that sub-Arctic invaders are likely modifying the marine fish species assemblages in proximity to northern communities. As more sub-Arctic species are identified in northern coastal communities, the power of Arctic endemics to differentiate among northern communities' fish assemblages will be lessened. This occurs because Arctic regions receiving a greater influx of southern species will cause them to be more dissimilar to those receiving fewer and that maintain their Arctic species complement (Scott and Helfman 2001). This is consistent with reports of changes to fish community composition occurring in other southern portions of the Arctic circle where sub-Arctic fish community traits are displacing typical Arctic fish community traits in increasingly northern latitudes (Frainer et al. 2021; von Biela et al. 2023; Levine et al. 2023). While no obvious geographical patterns were observed in fish species assemblages among communities here, this could be related to more than just latitude affecting fish assemblages among communities in the complex Archipelago of Arctic Canada (Roy et al. 2014). Other factors such as ocean topography, current patterns, and the number of individuals reaching a coastal area (i.e., propagule pressure) that regulate species invasions could also be at play along with thermal regime shifts (Michel et al. 2006). Future work could more closely sift through NCRIs (and other codified traditional knowledge) to identify whether diversity patterns reported in southern communities with greater instances of southern invaders are greater than those in more northern ones.

Overall, the cultural list contained a small number of species (25) mainly due to our statistical filters. Although including species observed in less than five communities might have generated a longer list, the low observation counts of those species would have weakened our results and consistently placed those species near the bottom of the cultural list (analyses not shown). Knowledge from other Arctic Indigenous communities from Nunavik (Quebec), Inuvialuit

(Northwest Territories), Kalaallit Nunaat (Greenland), Alaska, Sápmi (northern Europe), and Russia was not available in a standardized form to our knowledge and therefore is not accounted for.

In terms of conservation management, many species on the cultural list remain unassessed or are data limited. Shorthorn sculpin's Arctic population has not been assessed despite its ecological (Herman et al. 2023) and cultural importance, and its vulnerability to increasing vessel traffic (Ivanova et al. 2018). Greenland shark is a data-deficient, long-lived species, often encountered by Inuit, and vulnerable to increased fishery exploitation (Madigan et al. 2022). Yet, logistical challenges remain an obstacle to establishing a management program for this species (Edwards et al. 2019). While marine fish comprise only a small proportion of Indigenous nutrition (Rapinski et al. 2018), they are nevertheless a key component of mid-trophic levels upon which many predators such as Arctic char, seals, and whales ─ which are directly culturally important ─ are dependent. As such, the conservation of diverse marine fishes is crucial to maintaining the cultural traditions of northern communities.

3.5.4 Combined list

Our methodology bridges ecological, economic, and cultural perspectives on Arctic marine fish importance to which can be useful to prioritize an actionable list of species for conservation based on currently available knowledge. Each perspective provides unique, but also complementary insights into the importance of marine fishes in the Arctic. The combined list highlights the advantage of integrating various knowledge types to identify a diversity of important species. While our finalized list of 148 species identified some as important across perspectives, others were unique to only one perspective. Among these, we identified 27 endemic Arctic fishes (i.e., species whose major distributions are above the Arctic Circle), most of which were ranked in the top half of the list. The remainder of the list consisted of sub-Arctic (Atlantic and/or Pacific) species, supporting the many reports on the encroachment of sub-Arctic species into Arctic ecosystems. Such invasions will most likely shift ecosystem dynamics into alternative stable states, with consequences for ecosystem resiliency that are difficult to predict. As for the conservation context of these crucial fishes, their IUCN and COSEWIC statuses generally coincided for species whose range includes Canadian seas. Nevertheless, Canadian Greenland halibut and Walleye pollock populations have not yet been evaluated despite their IUCN 'Near threatened' designations. To help better understand those consequences, we urgently need to develop additional biological information and conservation monitoring tools for Arctic fishes. Our multi-perspective methodology identified important Arctic fish species, many of which should be prioritized, including those (e.g., Arctic cod, Polar cod, Shorthorn sculpin, etc.) for which their conservation status and/or population trends have yet to be evaluated. Through using diet composition information from the literature, economic forecasts based on historical trends, and sources of traditional and local knowledge from Inuit observations, we provide a starting point for directing future fish research and conservation of Arctic marine fish biodiversity.

3.6 Acknowledgements

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3.7 Figures and Tables

Table 1. Combined importance list of marine fishes bridging ecological, economic, and cultural perspectives. Arctic species bolded. Presented summed importance scores rounded to the nearest significant digit. IUCN Red List and COSEWIC conservation statuses listed to provide modern international and Canadian management context, respectively.

Final rank	Species	Latin binomial	Summed importance score	IUCN Red List conservation status (population trend)	COSEWIC status
1	Atlantic cod	*Gadus morhua*	1.04	Vulnerable (*)[a]	Data deficient
2	**Arctic cod**	*Boreogadus saida*	0.85	Least concern (?)[b]	Not evaluated
3	Capelin	*Mallotus villosus*	0.75	Least concern (?)	Not evaluated
4	**Walleye pollock**	*Gadus chalcogrammus*	0.74	Near threatened (?)	Not evaluated
5	Atlantic herring	*Clupea harengus*	0.66	Least concern (+)[c]	Not evaluated
6	**Greenland halibut**	*Reinhardtius hippoglossoides*	0.61	Near threatened (-)[d]	Not evaluated
7	**Polar cod**	*Arctogadus glacialis*	0.54	Not evaluated	Not evaluated
8	**Shorthorn sculpin**	*Myoxocephalus scorpius*	0.45	Least concern (?)	Not evaluated
9	Sand lance	*Ammodytes* spp.	0.36	Not evaluated	Not evaluated
10	**Greenland shark**	*Somniosus microcephalus*	0.35	Vulnerable (-)	Not evaluated
11	Lumpsucker	*Cyclopterus lumpus*	0.28	Near threatened (?)	Threatened
12	**Arctic staghorn sculpin**	*Gymnocanthus tricuspis*	0.27	Least concern (?)	Not evaluated
13	**Greenland cod**	*Gadus ogac*	0.26	Not evaluated	Not evaluated
14	Blue whiting	*Micromesistius poutassou*	0.25	Least concern (?)	Not evaluated
15	Haddock	*Melanogrammus aeglefinus*	0.24	Vulnerable (*)	Not evaluated
16	Pacific herring	*Clupea pallasii*	0.20	Data deficient (?)	Not evaluated
17	Golden redfish	*Sebastes norvegicus*	0.20	Vulnerable (-)	Not evaluated
18	**Saffron cod**	*Eleginus gracilis*	0.17	Not evaluated	Not evaluated
19	**Arctic eelpout**	*Lycodes reticulatus*	0.15	Least concern (?)	Not evaluated
20	Pollock	*Pollachius pollachius*	0.14	Least concern (?)	Not evaluated
21	**Arctic skate**	*Amblyraja hyperborea*	0.14	Least concern (?)	Not evaluated
22	**Arctic sculpin**	*Myoxocephalus scorpioides*	0.14	Not evaluated	Not evaluated

23	Saithe	*Pollachius virens*	0.12	Least concern (?)	Not evaluated
24	Pacific cod	*Gadus macrocephalus*	0.12	Not evaluated	Not evaluated
25	Northern hagfish	*Myxine glutinosa*	0.11	Least concern (?)	Not evaluated
26	Atlantic mackerel	*Scomber scombrus*	0.11	Least concern (-)	Not evaluated
27	Winter flounder	*Pseudopleuronectes americanus*	0.10	Vulnerable (-)	Not evaluated
28	**Twohorn sculpin**	*Icelus bicornis*	0.10	Least concern (?)	Not evaluated
29	Snakeblenny	*Lumpenus lampretaeformis*	0.07	Least concern (?)	Not evaluated
30	**Fourhorn sculpin**	*Myoxocephalus quadricornis*	0.07	Least concern (=)[e]	Not evaluated
31	**Hamecon**	*Artediellus scaber*	0.06	Not evaluated	Not evaluated
32	**Atlantic spiny lumpsucker**	*Eumicrotremus spinosus*	0.06	Data deficient (?)	Not evaluated
33	**Leatherfin lumpsucker**	*Eumicrotremus derjugini*	0.06	Not evaluated	Not evaluated
34	**Daubed shanny**	*Leptoclinus maculatus*	0.05	Least concern (?)	Not evaluated
35	**Thorny skate**	*Amblyraja radiata*	0.04	Vulnerable (-)	Special concern
36	**Bartail seasnail**	*Liparis tunicatus*	0.04	Not evaluated	Not evaluated
37	**Fourline snakeblenny**	*Eumesogrammus praecisus*	0.04	Not evaluated	Not evaluated
38	American plaice	*Hippoglossoides platessoides*	0.03	Endangered (-)	Data deficient
39	Ling	*Molva molva*	0.02	Least concern (?)	Not evaluated
40	Pacific halibut	*Hippoglossus stenolepis*	0.02	Least concern (=)	Not evaluated
41	Norway pout	*Trisopterus esmarkii*	0.02	Least concern (+)	Not evaluated
42	**Beaked redfish**	*Sebastes mentella*	0.02	Least concern (?)	Not evaluated
43	Sablefish	*Anoplopoma fimbria*	0.01	Not evaluated	Not evaluated
44	Pacific ocean perch	*Sebastes alutus*	0.01	Not evaluated	Not evaluated
45	European plaice	*Pleuronectes platessa*	0.01	Least concern (+)	Not evaluated
46	Yellowfin sole	*Limanda aspera*	0.01	Least concern (-)	Not evaluated
47	Atka mackerel	*Pleurogrammus monopterygius*	0.009	Not evaluated	Not evaluated
48	European sprat	*Sprattus sprattus*	0.009	Least concern (?)	Not evaluated
49	Atlantic wolffish	*Anarhichas lupus*	0.008	Data deficient (?)	Special concern
50	Atlantic halibut	*Hippoglossus hippoglossus*	0.007	Near threatened (-)	Not at risk
51	Tusk	*Brosme brosme*	0.007	Least concern (?)	Endangered

52	Atlantic horse mackerel	*Trachurus trachurus*	0.006	Vulnerable (-)	Not evaluated
53	Yellowtail flounder	*Myzopsetta ferruginea*	0.005	Vulnerable (-)	Not evaluated
54	Flathead sole	*Hippoglossoides elassodon*	0.004	Least concern (=)	Not evaluated
55	Whiting	*Merlangius merlangus*	0.003	Least concern (?)	Not evaluated
56	Roundnose grenadier	*Coryphaenoides rupestris*	0.003	Critically endangered (?)	Endangered
57	Witch flounder	*Glyptocephalus cynoglossus*	0.003	Vulnerable (-)	Not evaluated
58	**Northern wolffish**	*Anarhichas denticulatus*	0.003	Endangered (-)	Threatened
59	European hake	*Merluccius merluccius*	0.003	Least concern (?)	Not evaluated
60	Silver hake	*Merluccius bilinearis*	0.002	Near threatened (?)	Not evaluated
61	Blue ling	*Molva dypterygia*	0.002	Not evaluated	Not evaluated
62	Swordfish	*Xiphias gladius*	0.002	Near threatened (-)	Not evaluated
63	White hake	*Urophycis tenuis*	0.002	Not evaluated	Threatened
64	**Spotted wolffish**	*Anarhichas minor*	0.002	Near threatened (?)	Threatened
65	Lemon sole	*Microstomus kitt*	0.002	Least concern (=)	Not evaluated
66	**Alaska plaice**	*Pleuronectes quadrituberculatus*	0.002	Least concern (=)	Not evaluated
67	Blue shark	*Prionace glauca*	0.001	Near threatened (-)	Not at risk
68	Kamchatka flounder	*Atheresthes evermanni*	0.001	Least concern (+)	Not evaluated
69	Arrowtooth flounder	*Atheresthes stomas*	0.001	Least concern (=)	Not evaluated
70	Rex sole	*Glyptocephalus zachirus*	0.001	Least concern (=)	Not evaluated
71	Atlantic bluefin tuna	*Thunnus thynnus*	0.001	Least concern (?)	Endangered
72	Common sole	*Solea solea*	0.0009	Data deficient (=)	Not evaluated
73	Atlantic butterfish	*Peprilus triacanthus*	0.0009	Not evaluated	Not evaluated
74	Common dab	*Limanda limanda*	0.0008	Least concern (+)	Not evaluated
75	Basking shark	*Cetorhinus maximus*	0.0007	Endangered (-)	Endangered
76	**Roughhead grenadier**	*Macrourus berglax*	0.0006	Least concern (-)	Not at risk
77	American angler	*Lophius americanus*	0.0005	Not evaluated	Not evaluated
78	European flounder	*Platichthys flesus*	0.0004	Least concern (-)	Not evaluated
79	Greater argentine	*Argentina silus*	0.0004	Least concern (+)	Not evaluated
80	Cunner	*Tautogolabrus adspersus*	0.0004	Least concern (?)	Not evaluated
81	Atlantic silverside	*Menidia menidia*	0.0003	Least concern (=)	Not evaluated

82	Atlantic saury	*Scomberesox saurus*	0.0002	Least concern (?)	Not evaluated
83	Grey gurnard	*Eutrigla gurnardus*	0.0002	Least concern (?)	Not evaluated
84	Black scabbardfish	*Aphanopus carbo*	0.0002	Least concern (?)	Not evaluated
85	Megrim	*Lepidorhombus whiffiagonis*	0.0002	Least concern (+)	Not evaluated
86	Norway redfish	*Sebastes viviparus*	0.0002	Least concern (?)	Not evaluated
87	Turbot	*Scophthalmus maximus*	0.0001	Least concern (-)	Not evaluated
88	Red hake	*Urophycis chuss*	0.0001	Not evaluated	Not evaluated
89	Lingcod	*Ophiodon elongatus*	0.0001	Not evaluated	Not evaluated
90	Ocean pout	*Zoarces americanus*	0.0001	Not evaluated	Not evaluated
91	Blue skate	*Dipturus batis*	0.00008	Critically endangered (-)	Not evaluated
92	Greater weever	*Trachinus draco*	0.00008	Least concern (?)	Not evaluated
93	Scup	*Stenotomus chrysops*	0.00008	Near threatened (-)	Not evaluated
94	Bigeye tuna	*Thunnus obesus*	0.00007	Vulnerable (-)	Not evaluated
95	Yellowfin tuna	*Thunnus albacares*	0.00006	Least concern (-)	Not evaluated
96	Summer flounder	*Paralichthys dentatus*	0.00005	Least concern (-)	Not evaluated
97	Brill	*Scophthalmus rhombus*	0.00004	Least concern (=)	Not evaluated
98	Little skate	*Leucoraja erinacea*	0.00004	Least concern (+)	Not evaluated
99	Tub gurnard	*Chelidonichthys lucerna*	0.00003	Least concern (?)	Not evaluated
100	European anchovy	*Engraulis encrasicolus*	0.00003	Least concern (-)	Not evaluated
101	Atlantic pomfret	*Brama brama*	0.00003	Least concern (?)	Not evaluated
102	Atlantic sailfish	*Istiophorus albicans*	0.00002	Not evaluated	Not evaluated
103	Rabbit fish	*Chimaera monstrosa*	0.00002	Vulnerable (-)	Not evaluated
104	Poor cod	*Trisopterus minutus*	0.00002	Least concern (?)	Not evaluated
105	Petrale sole	*Eopsetta jordani*	0.00001	Least concern (=)	Not evaluated
106	Black rockfish	*Sebastes melanops*	0.00001	Not evaluated	Not evaluated
107	Leafscale gulper shark	*Centrophorus squamosus*	0.00001	Endangered (-)	Not evaluated
108	Garfish	*Belone belone*	0.000009	Least concern (?)	Not evaluated
109	Black cardinalfish	*Epigonus telescopus*	0.000008	Least concern (?)	Not evaluated
110	**Baird's slickhead**	*Alepocephalus bairdii*	0.000006	Data deficient (?)	Not evaluated
111	Atlantic bonito	*Sarda sarda*	0.000005	Least concern (=)	Not evaluated
112	John dory	*Zeus faber*	0.000004	Data deficient (=)	Not evaluated

113	Mediterranean scaldfish	*Arnoglossus laterna*	0.000004	Least concern (?)	Not evaluated
114	Threadfin rockling	*Gaidropsarus ensis*	0.000004	Not evaluated	Not evaluated
115	Blue antimora	*Antimora rostrata*	0.000003	Least concern (?)	Not evaluated
116	Bluefish	*Pomatomus saltatrix*	0.000003	Vulnerable (-)	Not evaluated
117	English sole	*Parophrys vetulus*	0.000003	Least concern (+)	Not evaluated
118	Red gurnard	*Chelidonichthys cuculus*	0.000003	Least concern (?)	Not evaluated
119	Pacific tomcod	*Microgadus proximus*	0.000002	Not evaluated	Not evaluated
120	Atlantic white marlin	*Kajikia albida*	0.000002	Least concern (+)	Not evaluated
121	Pouting	*Trisopterus luscus*	0.000002	Least concern (?)	Not evaluated
122	Blackspot seabream	*Pagellus bogaraveo*	0.000002	Near threatened (-)	Not evaluated
123	Canary rockfish	*Sebastes pinniger*	0.000002	Not evaluated	Threatened
124	Atlantic menhaden	*Brevoortia tyrannus*	0.000002	Least concern (+)	Not evaluated
125	Red mullet	*Mullus barbatus*	0.000001	Least concern (?)	Not evaluated
126	Widow rockfish	*Sebastes entomelas*	0.000001	Not evaluated	Not evaluated
127	Great barracuda	*Sphyraena barracuda*	0.000001	Least concern (?)	Not evaluated
128	Blackbelly rosefish	*Helicolenus dactylopterus*	0.000001	Least concern (?)	Not evaluated
129	Tiger shark	*Galeocerdo cuvier*	0.000001	Near threatened (-)	Not evaluated
130	Oilfish	*Ruvettus pretiosus*	0.0000009	Least concern (=)	Not evaluated
131	Yellowtail rockfish	*Sebastes flavidus*	0.0000008	Not evaluated	Not evaluated
132	Starry flounder	*Platichthys stellatus*	0.0000004	Least concern (=)	Not evaluated
133	Fourbeard rockling	*Enchelyopus cimbrius*	0.0000003	Least concern (?)	Not evaluated
134	Common dolphinfish	*Coryphaena hippurus*	0.0000002	Least concern (=)	Not evaluated
135	European pilchard	*Sardina pilchardus*	0.0000002	Least concern (?)	Not evaluated
136	Longnose skate	*Beringraja rhina*	0.0000002	Least concern (=)	Not at risk
137	Pacific saury	*Cololabis saira*	0.0000001	Not evaluated	Not evaluated
138	Skipjack tuna	*Katsuwonus pelamis*	0.0000001	Least concern (-)	Not evaluated
139	Smallspotted catshark	*Scyliorhinus canicula*	0.0000001	Least concern (=)	Not evaluated
140	Blue marlin	*Makaira nigricans*	0	Vulnerable (-)	Not evaluated
141	Bocaccio rockfish	*Sebastes paucispinis*	0	Critically endangered (*)	Endangered
142	Darkblotched rockfish	*Sebastes crameri*	0	Not evaluated	Special concern
143	European conger	*Conger conger*	0	Least concern (+)	Not evaluated

144	Greater forkbeard	*Phycis blennoides*	0	Data deficient (?)	Not evaluated
145	Longfin mako	*Isurus paucus*	0	Endangered (-)	Not evaluated
146	Rock sole	*Lepidopsetta bilineata*	0	Least concern (=)	Not evaluated
147	Rough scad	*Trachurus lathami*	0	Least concern (=)	Not evaluated
148	Silvery lightfish	*Maurolicus muelleri*	0	Least concern (?)	Not evaluated

[a] * represents an unspecified population trend
[b] ? represents an unknown population trend
[c] + represents a positive population trend
[d] - represents a negative population trend
[e] = represents a stable population trend

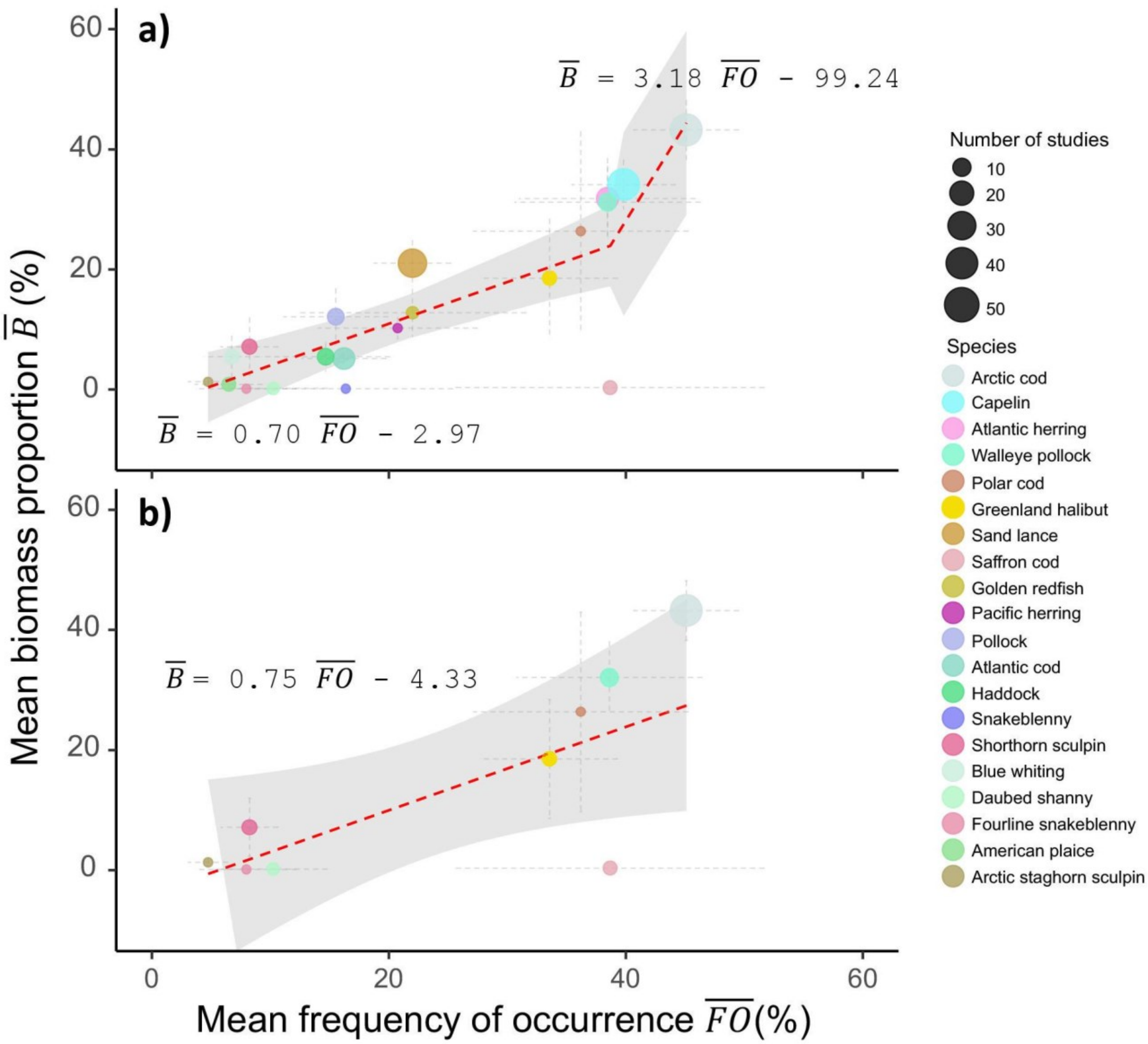

Figure 1. a) Mean frequency of occurrence and biomass proportion (± SE) of the most prevalent and consumed fishes in Arctic predator diets. Bubbles show species, with size reflecting number of peer-reviewed sources from which data originates. Red dashed line outlines best relationships. Threshold at which relationship shifts = 38.68% ± 4.12, 24.11% ± 8.31. b) The same as in a but applied only to Arctic endemic fishes.

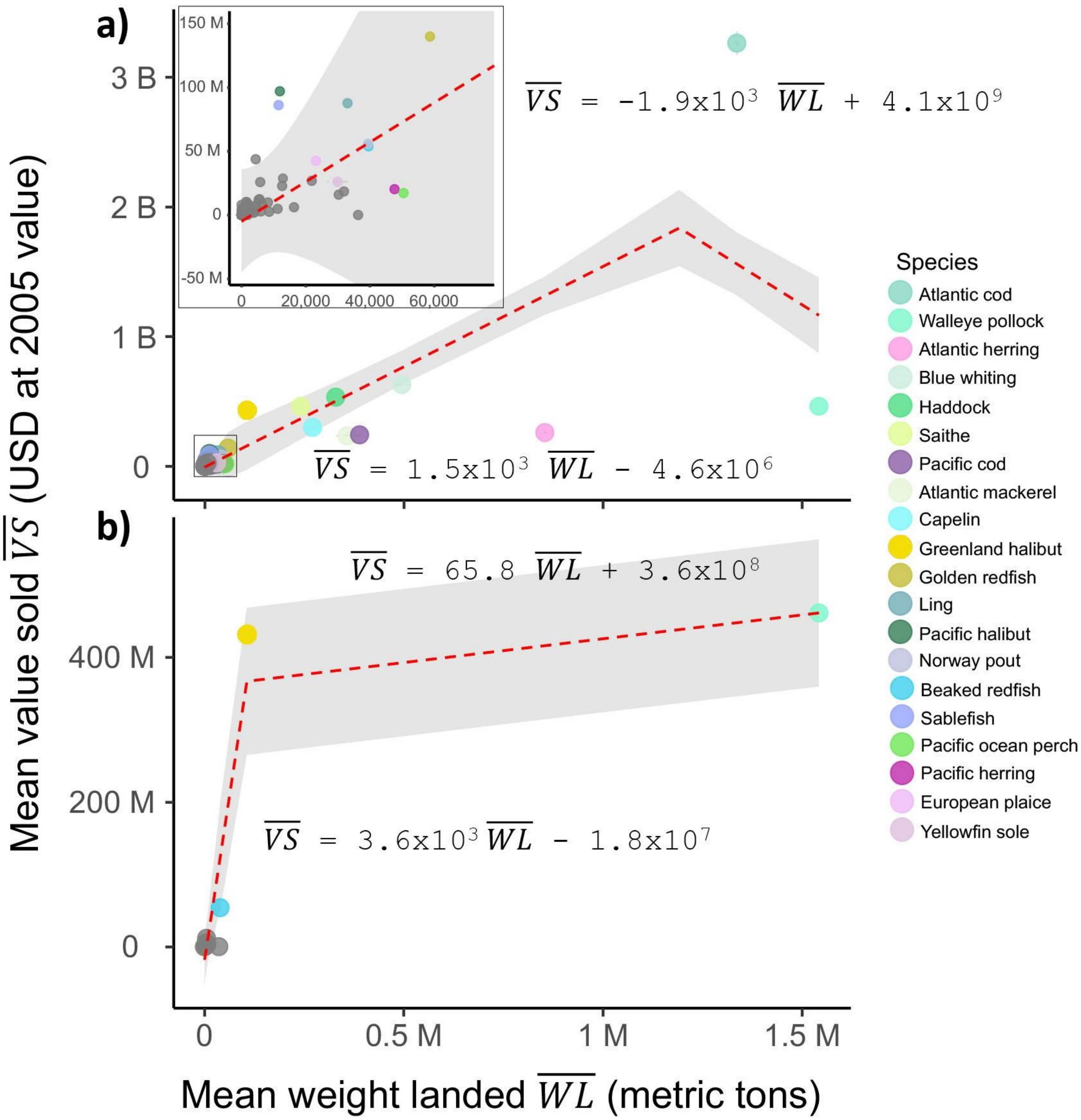

Figure 2. Mean forecasted weight landed and value sold for, a) overall species in Arctic and sub-Arctic areas, and b) Arctic endemic species. Data are predicted from 2015–2034 in the Exclusive Economic Zones of the United States (Alaska), Canada, Iceland, Denmark (Greenland and the Faroe Islands), Norway (including Jan Mayen and Svalbard Islands), and Russia. Red dashed line (and 95% CI) outlines best relationship. Threshold at which relationship shifts in a = $1.19 \times 10^6 \pm 1.18 \times 10^5$ metric tons, $1.84 \times 10^9 \pm 2.21 \times 10^7$ USD at 2005 value. Threshold at which

relationship shifts in b = $1.06 \times 10^5 \pm 3.41 \times 10^4$ metric tons, $3.67 \times 10^8 \pm 6.29 \times 10^7$ USD at 2005 value. Note different y-axes scales in a) and b). Points show species where only the top 20 are coloured with the rest in grey.

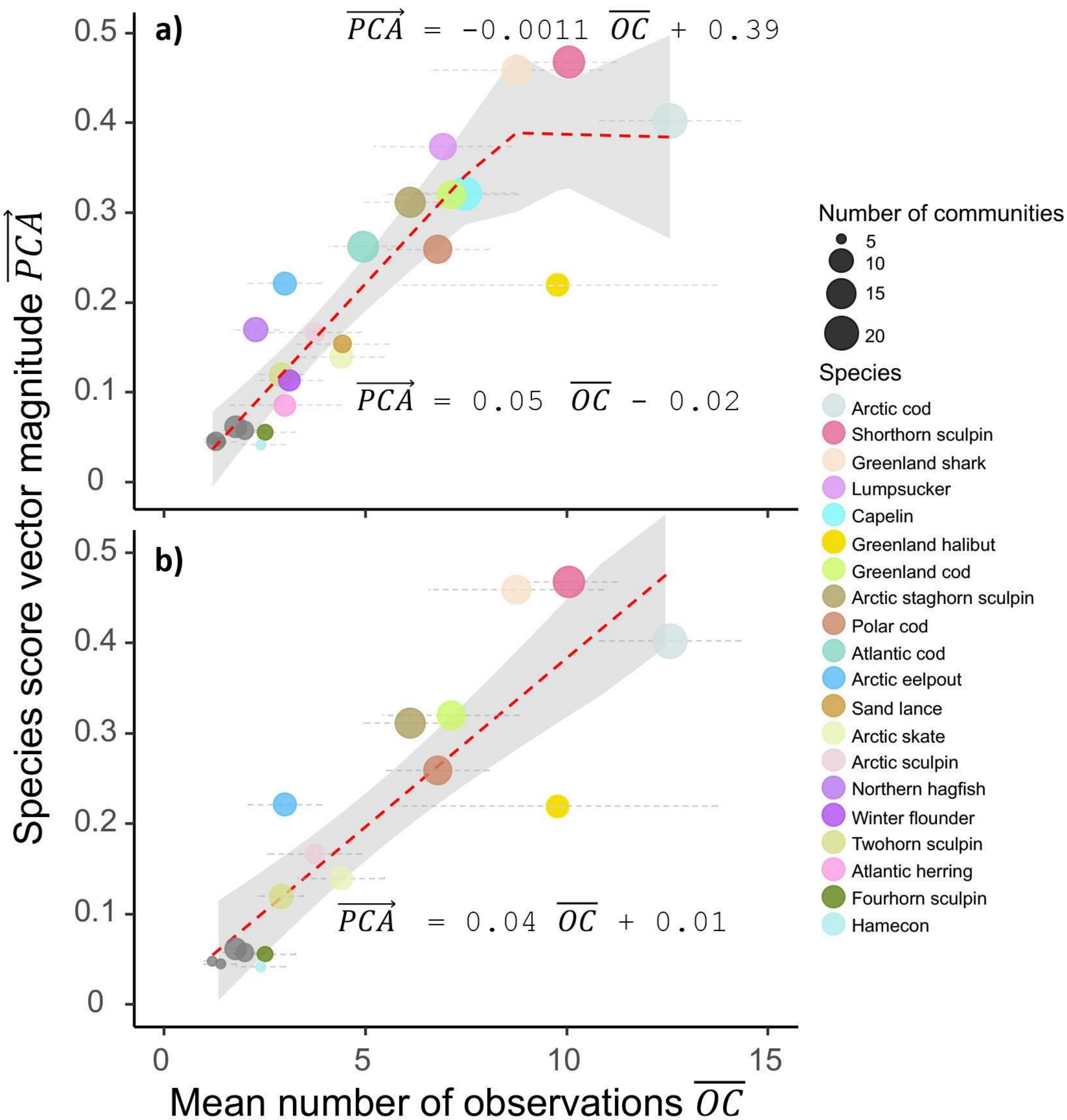

Figure 3. a) Mean number of observations (± SE) and species score vector magnitude (using PC1 and 2) for all species, and (b) for Arctic endemic species mentioned in the NCRIs. Bubbles represent species, with size reflecting number of communities reporting them. Red dashed line (and 95% CI) outlines best relationship. Threshold at which relationship shifts = 8.47 ± 1.21

observations, 0.40 ± 0.09 species score vector magnitude. Points show species where only the top 20 are coloured with the rest in grey.

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Chapter 4: Synthesis

4.1 Bridging text

I am particularly proud of my systematic literature search and data compilation on Arctic predator diets. The resulting database is the result of a large effort to collate all available quantitative data on Arctic predator diet that identified prey at the species level, which many studies forego nowadays in favour of biochemical techniques (i.e., via fatty acids, DNA metabarcoding) because the identification of stomach contents is laborious and time intensive. The database contains the reported figures from 84 different literature sources and details the diet of 30 Arctic predators, identifying 107 different prey. While not used in the manuscript analyses, each observation also contains information on sample size, numerical frequency, energetic contribution estimates, sampling years, sampling season, and geographical region (Hudson Bay, Greenland Sea, Baffin Bay, Nunavut, Beaufort Sea, Chukchi Sea, Bering Sea, or Barents Sea) when they were available to extract from the selected articles. The inclusion of temporal and spatial dimensions in the data could provide the basis for such types of analyses. In particular, these data could potentially shed light on temporal changes to predator diets across Arctic and sub-Arctic circumpolar regions.

I will also be uploading my analysis scripts to open-source repositories (Github, McGill Dataverse), which could help researchers looking to reproduce my methodology, further widening the potential exposure of my work at an international level (see final publication of the manuscript for details). I am particularly proud of the solution I found to automate 130 time series analyses as well as the recording and illustration of their results, saving me a significant amount of time and labor. These resources could be helpful to other researchers less familiar with programming in R.

4.2 Discussion

The objective of building a combined importance list of Arctic marine fish by leveraging ecological, economic, and cultural knowledge to prioritize understudied species for conservation was met, albeit with various important caveats. To achieve this, I systematically surveyed the literature for information on Arctic piscivorous predator diets, forecasted Arctic and sub-Arctic fisheries catches and value time series ten years into the future, and extracted Inuit traditional and local knowledge about species occurrence and contribution to community dissimilarity. To bring these perspectives together, I then present an interdisciplinary list of Arctic marine fish importance which can be used to determine which species to focus research and conservation efforts on to conserve biodiversity, and thus ecosystem function.

The contribution of this thesis to the field of Arctic marine ecology and conservation is hopefully a cohesive, integrative importance list that bridges different knowledge types and helps identify which fishes to prioritize for conservation given limited time and resources. My results support the widespread reports of the Southernization of Arctic marine ecosystems by presenting evidence that Atlantic and Pacific species have become integral parts of Artic food webs and economies, although cultural attitudes towards these invasive species are taking more time to change. However, they are indeed changing, as the case of Pacific salmon detailed in the Introduction clearly illustrates. Furthermore, my results also highlight the overall dearth of information about several crucial endemic Arctic marine species such as Arctic cod, polar cod, and shorthorn sculpin. According to the IUCN Red List, most Arctic fish on my combined importance list were either threatened to some degree, data deficient, assessed based on the few data available, or unassessed. This thesis also details a reproducible methodology that could be applied to other ecosystems (e.g., tropical, temperate, etc.) to determine fish species importance given access to diet studies, catch reconstructions, and local Indigenous knowledge.

Tailoring an ideal search string for the systemic literature search was surprisingly more difficult than I expected. With my first iterations, results about the predators of the fish I was researching (especially polar bears) kept resurfacing in my searches instead of articles about the prey proper. With some experimentation, I found a modification that could discard articles about the most common Arctic predators reported in the literature: filtering any article with mentions of pollutants such as per- and polyfluorinated substances, emerging brominated flame-retardants, organophosphate ester, polychlorinated biphenyls or parasites. With this addition, I was able to reduce the amount of hits I was obtaining from my searches without compromising my ability to find diet studies.

Finding appropriate criteria to include fisheries bordering the Arctic in the economic analysis was not a straightforward task. Had I only included figures for fisheries strictly in the central Arctic Ocean (CAO; FAO zone 18), I would have missed many emerging fisheries that depend on species which spend only part of their lives in Arctic seas (e.g., Walleye pollock, Beaked redfish, etc.). Additionally, catches in the CAO are substantially underreported and thus do not provide a sufficiently confident baseline with which one can meaningfully predict future demand (Zeller et al. 2011). To deal with this issue, certain maritime authorities such as NAFO and ICES have defined delimited regions in the North Atlantic to more accurately tally catches made close to the Arctic, but which might not necessarily fall into the defined CAO zone. This initiative represents a step in the right direction regarding better monitoring and enforcement policies that are more based on ecological relevancy (i.e., species distributions) than geographic separation (i.e., Arctic, Atlantic, Pacific, etc.). Since I wanted to consider circumpolar catches and data on analogous zones in the North Pacific are not available, I did not make use of these zones. As the NOEP database only categorized catches by FAO zone, I was forced to choose between extracting only Arctic data (unreliable, as discussed above) or Arctic and sub-Arctic data. Therefore, I decided to include sub-Arctic catches from the Northwest and Northeast Atlantic and Pacific (FAO zones 21, 27, 61, and 67) despite the resulting inclusion of many fisheries outside the Arctic. While this did add a lot of non-Arctic species to the economic list, it also managed to capture emergent Arctic-adjacent fisheries such as Walleye pollock's. If I had used strictly CAO data, I wouldn't have captured these important fisheries in Arctic-adjacent seas (e.g., Baffin Bay, Northern Europe, Canadian Arctic Archipelago, etc.).

The NCRIs showed diverse fish assemblages across communities in the Arctic. This could have substantial consequences on how conservation and management is approached for Arctic fishes. Widespread species found across most/all communities could be monitored with genomics tools to reduce workload while fishes with more constrained ranges might necessitate individual tagging using catch and release methods. Unanswered questions also remain about the sustainability of potential Arctic and Arctic-adjacent fisheries. What kind of exploitation rates will be sustainable? Will fishing the invasive species to local extirpation reduce the negative effects of increased competition with resident species? What are the conservation consequences for endemic and invasive species in Arctic ecosystems? We need to further assess how these Atlantic and Pacific fish are moving into the Arctic by developing and deploying remote monitoring tools. For example, the development of genomic tools can provide a cost effective and efficient way to estimate many important population parameters relatively quickly from just a few surveys (Colella et al. 2020; Dallaire et al. 2021; Layton et al. 2021). Electronic tagging techniques could also provide information on habitat use and movement for fishes with less developed genomes (Jepsen et al. 2015; Hussey et al. 2017). At a regional scale, Marine Protected Areas help protect Arctic habitats and species due to their large-scale restrictions on human exploitation and industry, with three Areas established in 2010 (Tarium Niryutait), 2016 (Anguniaqvia niqiqyuam), and 2019 (Tuvaijuittuq; DFO 2024). Different species assemblages across Arctic communities and the diversity of environments that these fishes are adapted to will likely necessitate locally relevant approaches to management. For example, communities with more benthic species might need to employ electronic tagging techniques versus communities with more pelagic species, which might be able to survey the water column near the surface using hydroacoustic methods. For now, the International Moratorium on High Arctic Commercial Fishing is still in place, prohibiting harvest in High Arctic seas until 2034, providing international researchers an opportunity to better understand these ecosystems. Regardless, Arctic marine ecosystems may not be able to act as refugia for invasive species or resilient enough to withstand increasing commercial exploitation due to rapidly changing conditions.

Finding a way to analyze and interpret the cultural data respectfully and faithfully without Indigenous co-authors was a major challenge in the undertaking of the project. As I learned from this project and literature on co-developing knowledge, relationships between academics and

Indigenous stakeholders are built over time and through close collaboration, the former of which I was very short of and the latter of which I did not have the financial resources to accomplish. While collecting fish importance data from northern communities by contacting local hunters and trappers' organizations, or through organized community meetings and/or surveys would have been more direct, the costs and logistic challenges of doing so over many northern coastal communities are not trivial. Such an endeavour would require a large-scale collaboration among Arctic researchers, various governance structures, and members of multiple communities, spanning large geographic regions, and be produced at considerable costs. However, public sources of rarely codified Indigenous Knowledge such as the Nunavut Coastal Resource Inventories are helping to provide novel ways for scientists to engage with Indigenous knowledge in their research. This work shows that recognizing the value of Indigenous knowledge can provide insight into the distribution of otherwise data-deficient Arctic marine fishes.

While we excluded anadromous fishes from our cultural analysis, their importance to Indigenous Peoples cannot be understated. For millennia, Indigenous communities in the Arctic have depended on anadromous fishes that spend a component of their lives in marine systems such as Arctic char, Arctic cisco, and various species of salmon. My focus on strictly marine fishes was only decided on to narrow the already very large scope of investigation of the overall thesis, with a recognition that anadromous fishes could represent an important avenue for future investigations. As I used publicly available data, other researchers could perform similar analyses with an anadromous focus to target important but understudied fishes in need of conservation attention.

Merging the lists was another challenge that I faced when trying to integrate different knowledge types. The main difficulty stemmed from two issues I encountered when running my analyses and obtaining an initial list for each perspective (ecology, economy, culture): a) the list produced by each analysis was of a different length because the amount of initial data for each analysis varied, and b) the lists could not be ordered strictly using post-hoc permutational multivariate analysis of variance (PERMANOVA) tests because not all list-adjacent (e.g., #1 and #2, #2 and #3, etc.) pairs of species were significantly different. I addressed these issues by normalizing the importance indices and averaging them, providing a single score for each fish, thus nullifying the difficulty stemming from merging lists of different lengths. To combine the lists, I summed the normalized score that each species was assigned in each perspective list, with the most important species having the highest overall scores. Species that were not selected for a list were inherently penalized since they would add zero to their score for each list they were missing from. This technique allowed me to form a final list combining multiple perspectives. Ties in overall scores between species were rare, only occurring near and at the end of the list, where certain species obtained a score of zero due to them only being identified in the economic list and having obtained negative weight and value forecasts. I interpreted these negative forecasts as equivalent to predictions of zero, as they essentially represent the same situation: the model forecasts that there will be no fish landed for that species within the given time frame.

As a first attempt at an interdisciplinary importance list of Arctic marine fish, my study has some limitations and biases. For the ecological analysis, I excluded any presence/absence, stable isotope, DNA metabarcoding data, and juvenile diet information because reconciling analyses was already one of my most significant challenges. Thus, I elected to focus on quantitative data for frequency of occurrence and biomass proportion of prey, limiting my analysis to the last meal or two of the fish, as only stable isotopes can give us an idea on the long-term diet of a species. In terms of my literature review, its large temporal scope (1970 to present) could introduce temporal variation associated with changes in assemblage structure throughout the years. Although community composition in Arctic and Arctic-adjacent seas has been steadily changing, especially throughout the last few decades (Andrews et al. 2019; Huntington et al. 2020; Levine et al. 2023), the studies included in my literature review actually reflect a 20-30-year timeline (as opposed to the planned 50-year timeline) because 58% of the studies were published post-2000 and 81% were published post-1990 (see Supplementary Material). While this might mitigate some bias, there likely remains some unaccounted temporal influence on the ecological analysis due to recent Southernization trends in species assemblage changes. However, the resulting ecological list only suggests a minor influence because most of the top species are well-known, important prey species for Arctic predators. As the economic analysis focuses on the 2015-2034 period, I could have focused on more recent diet trends, but with already limited data, this would drastically reduce my sample size of studies and compromise the statistical reliability of my results. Dynamic and/or bio-economic models, the often-preferred method due to its specificity to the life history of the fish, cannot, in many cases, be applied given the overall lack of even basic information on many Arctic marine fish (Van Pelt et al. 2017; Coad and Reist 2018; Snoeijs-Leijonmalm et al. 2020). Time series analyses also do not consider the end of the moratorium on fishing in the Arctic circle, at which point we could see a considerable increase in commercial fishing in that region due to new shipping lanes introducing increased traffic through the region (Tai et al. 2019; Steiner et al. 2024). My inability to conduct pan-Arctic in-person interviews with local Indigenous communities significantly limited the temporal and spatial scope of the traditional and local knowledge I hoped to gather. However, research fatigue is a commonly reported issue when conducting community-based research (Drake et al. 2023; Dominique Henri, pers. comm.), and thus I endeavoured to use knowledge that had already been collected by Indigenous scholars and knowledge keepers. The differing spatial scopes of each analysis (due to constraints by the amount of available information for each perspective) have also likely introduced some bias into the analyses. Each analysis considered slightly different geographical areas, with the ecological analysis encompassing a circumpolar Arctic scale, the economic analysis a circumpolar Arctic and sub-Arctic scale, and the cultural analysis a Canadian Arctic scale. If I had access to cultural knowledge from other Arctic Indigenous communities from around the globe, I might have identified more culturally important species that I missed focusing on the Canadian Arctic. The final list that we produce spans different scales depending on the amount of currently available data. Future iterations of these interdisciplinary analyses could integrate larger areas when more data becomes available for crucial but data-deficient fishes. By analyzing importance across perspectives using consistent spatial and temporal scales, one could provide more locally relevant results. Lastly, an important caveat of the thesis is that there are certainly species that are not on any of our lists due to a lack of knowledge about them under all three perspectives analyzed. Therefore, there are likely multiple critical species that are not captured by my methodology.

In the context of Arctic marine conservation, I believe this work could encourage more graduate students and early career scientists to start exploring interdisciplinarity in their research. As a society, we are moving towards a more holistic approach to solving complex problems, and this thesis represents my attempt at rethinking my scientific approach to include multiple ways of knowing. My results illustrate that bridging different types of knowledge can yield practical insights about species conservation, and this model could be applied to other ecosystems due to the inherent connection between Indigenous Peoples and their natural environment across the globe. In summary, this thesis succeeded in its objective of ranking Arctic marine fish importance based on ecological, economic, and cultural perspectives, based on the available information in the primary and secondary literature. The final list of species produced also provides an easily interpretable starting point for academics to target crucial but understudied Arctic species in their research such as Polar cod and Shorthorn sculpin. Physiological, ecological, and socio-ecological studies could be conceptualized by Arctic researchers based on the importance list produced by this work, helping to fill critical research gaps.

Chapter 5: Conclusion

I identified the most important Arctic marine fish by collecting data on and combining ecological, economic, and cultural knowledge. With this list, species for which basic life history knowledge and conservation resources are lacking can be prioritized for monitoring and/or management. Importantly, only 27 of the 148 species on the combined importance list are endemic to the Arctic and management plans are established for only four of these Arctic marine fish: Greenland halibut, Walleye pollock, Alaska plaice, and Beaked redfish. However, Arctic cod, Polar cod, and Shorthorn sculpin populations are not currently managed despite their demonstrated multifaceted importance but unknown population trends. Each knowledge type provided unique and complementary insight into the importance of Arctic marine fishes as each list identified species that were present in other lists but also unique ones only important under one perspective. Therefore, this work supports the idea that exploring interdisciplinary analyses can yield further insight into otherwise data-deficient species. I present here a first attempt at an interdisciplinary, international importance list of Arctic marine fish encompassing ecological, economic, and cultural perspectives. The methodology presented combines scientific knowledge with economic forecasts and codified sources of traditional and local knowledge to identify important fishes at a circumpolar scale. Despite the multidimensional importance of the species on the combined list for Arctic ecosystems and societies, many are either endangered to some level, have unknown population trends, are assessed on minimal data, or remain unassessed. Thus, my results highlight the need for more biological data collection and monitoring focus on crucial Arctic marine fishes that have thus far received little conservation attention and the establishment of their population trends and, ultimately, management plans.

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