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Food web-mediated interaction between marine mammals and fisheries in the Norwegian and Barents seas.

Lucas Johannes Bas

Master's thesis in Biology BIO-3950 May 2023

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Cover photograph: © Lucas Bas – A common dolphin gliding in the water

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Abstract

Ecological systems, such as marine ecosystems, are complex adaptive systems in which large scale system properties (e.g., trophic structure, energy flux patterns, etc.) emerge from interactions between ecosystem components or species. This makes them difficult to understand, predict, and model. The Norwegian and Barents Seas support multiple commercial fisheries, including those for herring, cod, and mackerel. Fisheries extract around 2.61 million tonnes of fish annually and marine mammals consume 11.7 million tonnes of fish and zooplankton annually in the region. The gradual change from conventional fisheries management towards ecosystem-based fisheries management (EBFM) requires that interactions and trade-offs between exploitation and conservation of fish and marine mammals be considered. Such trade-offs occurs when there is direct or food-web mediated competition for resources between fisheries and marine mammals. Recent diet studies suggest that there is limited direct competition between marine mammals and fisheries. Food-web mediated interactions may occur when mammals consume the prey of commercial fish species, or when fisheries target the prey of marine mammals, but evidence for such interactions is still lacking. Using Chance and Necessity modelling (CaN) we reconstruct possible dynamics of 12 trophospecies in the Norwegian and Barents Sea ecosystems during the period 1988-2021. The reconstructed dynamics are consistent with multiple observations of biomass, diet, consumption, and life-history characteristics of the species groups. We use these reconstructions to establish the level of empirical support for food-web mediated interactions between marine mammals and fisheries. The results of the model analysis indicate that there is limited evidence to support direct competitive interactions between marine mammals and fisheries in the Norwegian Sea, and mixed evidence for such interactions in the Barents Sea. The results showed that most direct interactions between the two groups were bottom-up driven, and that only demersal fish, aside from cod, demonstrated a direct competitive interaction. As for food-web mediated interactions, the model provided evidence in support of a competitive interaction between marine mammals and capelin, between marine mammals and Barents Sea fish, and between marine mammals and all fish included in the model domain. However, the analysis also revealed the presence of a bottom-up trophic control in the food-web mediated interactions, particularly involving capelin and juvenile herring as prey. Thus, our model results show the presence of both opportunistic feeding and food-web mediated competitive interactions in the Norwegian and Barents Sea ecosystem.

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List of abbreviations

HerringNS	Her
BlueWhitingNS	BW
MackerelNS	Mac
CodBS	Cod
PolarCodBS	Pol
HerringBS	Juv Her
CapelinBS	Cap
OtherDemersalBS	OD
MinkeWhale	MW
ToothedWhales	TW
OtherBaleenWhales	OBW
Seals	Seal
KrillNS	KrillNS
ZooPlanktonNS	ZooP
MesopelagicAndOtherNS	Meso
KrillBS	KrillBS
AmphipodsBS	Amphi
CopepodBS	Cope
BenthosBS	Benthos

1 Introduction

> Every ecosystem is a complex, dynamic network made up by a vast array of interdependent organisms and physical factors. If one element shifts even slightly, the whole system can change. […]
>
> There is no 'original' state in nature, no steady-state nature in the sense that a fixed set of characteristics holds true, like that of the law of gravity, always and everywhere. […] So the question is: If there is no original state, how can we judge what should be conserved and restored.
>
> Kobie Krüger, *Mahlangeni.*

Ecological systems, such as marine ecosystems, are complex adaptive systems (CAS; Levin, 1998) in which large scale system properties (e.g. trophic structure, energy flux patterns, etc.) emerge from interactions between ecosystem components or species. Such systems display complex and non-linear feedback mechanisms operating across multiple trophic and spatial-temporal scales (e.g., from bacteria to marine mammals, seconds to years and millimetres to ocean basin). Bearing in mind that the degree of observability of marine ecosystems is low and that stochastic events play an important role in shaping the dynamics in ecology (Hubbell, 2001; Segre et al., 2014), marine ecosystems are difficult to understand and predict, let alone model.

To address this issue, ecosystem management strategies have been implemented, often in marine environments, with a focus on assessing the ecosystem while considering its constituent species (McLeod & Leslie, 2009). However, a previous conducted study suggests that only 24 out of 1200 investigated marine fish stocks were actually managed with ecosystem processes in mind (Skern-Mauritzen et al., 2016). The authors demonstrated that current fisheries management strategies are primarily focused on single-species management, with little consideration given to broader ecosystem-level processes. An example of marine waters that are managed in this manner is the Norwegian and Barents Seas.

The Norwegian and Barents Seas are high latitude deep water and shelf ocean, respectively. They are heavily influenced by the relatively warm Atlantic water that flows from the southwest into the Norwegian Sea and on into the Barents Sea (Loeng & Drinkwater, 2007). Both the Norwegian and Barents Seas are influenced by cold Arctic water from the north, which enters

the Norwegian Sea via the East Icelandic current and the Barents Sea through the East Spitsbergen current.

The Norwegian and Barents Seas are highly productive marine ecosystems. Both seas have high a primary production, in the form of spring blooms, that is dependent on temperature (Harrison et al., 2013; Mignot et al., 2016; Sakshaug, 1997). The link between the primary production and higher trophic levels is through secondary production with abundant functional groups, such as copepods and krill. As the Atlantic water flows through the Norwegian Sea and up into the Barents Sea, it carries with it planktonic secondary producers. The Norwegian and Barents Sea therefor have a similar composition of secondary producers.

This secondary production in turn supports diverse and abundant fish stocks as well as marine mammals (Blanchet et al., 2019; Bogstad et al., 2015; ICES, 2022b, 2022c; Melle et al., 2004; Planque, Favreau, et al., 2022; Skern-Mauritzen et al., 2022a). These fish stocks use the Norwegian and Barents Seas as feeding and spawning grounds, and function as a link to higher trophic levels, consisting of other fish species, sharks, and marine mammals (Blanchet et al., 2019; Jakobsen & Ozhigin, 2011; Skjoldal & Sætre, 2004). In the Norwegian sea, these fish species include the Norwegian spring spawning herring (*Clupea herrengus*, Linnaeus 1758), blue whiting (*Micromesistius poutassou*, A. Rosso 1827), and Atlantic mackerel (*Scomber scombrus*, Linnaeus 1758) (Skjoldal & Sætre, 2004). In the Barents Sea, the specie include capelin (*Mallotus villosus*, Müller 1776), Atlantic cod (*Gadus morhua*, Linnaeus 1758), juvenile Norwegian spring spawning herring, and polar cod (*Boreogadus saida*, Lepechin 1774) (Jakobsen & Ozhigin, 2011).

For decades, the biomass of some fish stocks in these regions has been fluctuating. With their biomass ranging between 1 million tonnes to 11 million tonnes within the last three decades (ICES, 2022a, 2022b, 2022c). Alongside these changes, there has been a shift in fisheries management from a single-species approach to an ecosystem-based fisheries management (EBFM) approach, the latter of which tries to balance between competing demands for service derived from harvested species in commercial fisheries, and those derived ecologically from species' roles in the food web interactions (Browman & Stergiou, 2004; Leslie & McLeod, 2007; Miljøverndepartementet, 2006). Thus, EBFM approaches are needed in marine systems

to anticipate possible interactions and trade-offs between the dietary needs of marine mammals and fishing activities.

Marine mammals play an important role in the Norwegian and Barents Seas, both as predators and as a target for human exploitation (Blanchet et al., 2019; Bogstad et al., 2015; W. D. Bowen & Lidgard, 2013; Skern-Mauritzen et al., 2022a). Within the Norwegian and Barents Sea ecosystem, the marine mammals feed on lipid-rich zooplankton and pelagic and demersal fish species, consuming a total of 11.7 million tonnes. With the most notable consumers minke whale (*Balaenoptera acutorostrata*, Lacépède 1804), fin whale (*Balaenoptera physalus*, Linnaeus 1758), humpback whale (*Megaptera novaeangliae*, Borowski 1781), Lagenorhynchus dolphins (*Lagenorhynchus albirostris*, Gray 1846 and *Lagenorhynchus acutus,* Gray 1828) and harp seal (*Pagophilus groenlandicus*, Erxleben 1777) (Skern-Mauritzen et al., 2022a). The marine mammals are attracted to the ecosystem because of the high primary productivity, which has led to an extensive zooplankton community and large fish stocks. As autumn progresses in the Norwegian Sea, large numbers of Norwegian spring spawning herring find shelter for the winter in the Norwegian coastal fjord system. This gathering makes for the perfect hunting grounds for humpback and killer whales (Jourdain & Vongraven, 2017; Vogel et al., 2021). Hunting alongside these seasonal visitors to the ecosystem are a resident group of predator species, namely seals. With the harp seal (*Pagophilus groenlandicus*) being the most conspicuous predator within the seal group. The ecosystem also encompasses other seal species such as the hooded seal (*Cystophora cristata*, Erxleben 1777) and bearded seal (*Erignathus barbatus*, Exleben 1777), both of which are subjected to hunting activities. Moreover, the Barents Sea ecosystem is known to have hunting activities for several other marine mammal species including minke whales, harp seals, grey seals (*Halichoerus grypus,* Fabricius 1791), and ringed seals (*Pusa hispida,* Schreber 1775).

Fisheries is arguably the most important direct driver of ecosystem change in marine ecosystems over the last century, affecting the structure, function, and biodiversity (Araújo & Bundy, 2012; Halpern et al., 2008; Jackson et al., 2001). Within the Norwegian and Barents Seas, the total annual catch by fisheries is 2.61 million tonnes, making it 4.5 times lower than the annual consumption of marine mammals (Skern-Mauritzen et al., 2022a). The fish stocks that are heavily fished are adult Norwegian spring spawning herring, blue whiting, Atlantic mackerel, Atlantic cod, and when in high abundance capelin (ICES, 2022b, 2022c). The

fisheries industry plays an important role for the Norwegian economy as seafood is the country's second-largest export, after oil and gas (Hjellnes et al., 2020).

Even with the vastly different quantity of removed biomass between the marine mammals and the fisheries, it is the task of EBFM to highlight and foresee potential interactions and trade-offs between them (Arthur et al., 2018; Browman & Stergiou, 2004; Chasco et al., 2017; Plagányi & Butterworth, 2009; Riisager-Simonsen et al., 2020; Trites et al., 1997). The interaction is typically displayed as a direct competitive interaction that is largely system specific, depending on a variety of factors. These factors include prey trophic level overlap, ecosystem complexity, and harvest intensity (Kaschner & Pauly, 2005a; Mackinson et al., 2003; Morissette et al., 2012; Skern-Mauritzen et al., 2022a). Modelling studies have suggested that direct competition is possible when the fisheries and marine mammals target species within the same or overlapping trophic levels. The depletion of prey stocks to critical levels by marine mammals, similar to other predators, is generally considered to be rare. The same cannot be said of the fishing industry. However, it is important to note that the recovery of fish stocks that have been depleted due to overfishing may be hindered by the predation pressure of marine mammals (Bundy et al., 2009; Cook & Trijoulet, 2016; Morissette et al., 2012). Thus, interaction is not straightforward, and quantifying the effects of marine mammals and fisheries on one another has posed a challenge for research in this field (Mackinson et al., 2003; Morissette et al., 2012; Pedersen et al., 2021)

To date, research regarding the consumption of marine mammals in the Norwegian and Barents Seas has primarily concentrated on a limited number of commercially exploited species, including common minke whales and harp seals (Bogstad et al., 2000; Lindstrøm et al., 2009; Windsland et al., 2008). Furthermore, the research has mostly been limited to examining the consumption of only a select few fish species, such as Northeast Atlantic cod, mackerel, herring, and capelin (Bogstad et al., 2000; Lindstrøm et al., 2009). When previous investigations of consumption by marine mammals and catch of fish stocks by fisheries have taken place, no firm conclusion was able to be drawn regarding a potential direct competitive interaction. Given the diverse range of marine mammal species inhabiting these ecosystems and a wide diet range, in conjunction with the substantial quantities and varieties of fishery removals, a more comprehensive evaluation of marine mammal-fisheries interactions is warranted.

In comparison to the average annual fisheries catch marine mammals have a total average annual consumption that is almost 5 times higher. This indicates that marine mammals play a significant role in determining the energy flow through the food web in these regions and have done so in the past (Skern-Mauritzen et al., 2022a). Moreover, the fisheries are targeting species with high food-web connectivity, which can have implications beyond the targeted species, potentially affecting the broader ecosystem. This results in a relationship between marine mammals and fisheries that may extend beyond direct competition and have the potential for a food-web-mediated interaction. This has been suggested in previously conducted studies, but evidence for it in the Norwegian and Barents Seas over the past decades is still lacking (Jog et al., 2022; Morissette et al., 2012; Schweder et al., 2000).

To better understand these food-web-mediated effects between marine mammals and the fisheries models are needed to investigate mammal-fisheries' direct and indirect interaction over the past few decades.

The objectives of this study are twofold. Firstly, I aim to reconstruct a collection of possible trajectories of the Norwegian and Barents Sea food webs, spanning the last three decades, in compliance with existing data and knowledge. Secondly, I aim to analyse whether the biomass of marine mammals in the Norwegian and Barents Seas was affected by changes in prey biomass driven by fisheries catch and vice versa over the past 35 years. This study will be looking at the correlation between consumption and removal over the entire period using a "Chance and Necessity" modelling approach (CaN, Planque & Mullon, 2020).

CaN is a modelling approach that is analogous to linear inverse modelling (LIM), such as Ecopath. However, CaN is a dynamic model that accounts for "Chance, i.e., the stochasticity of nature, and for Necessity, i.e., the existence of physical (e.g., mass conservation) or ecological (e.g., inertia of populations, satiation of individuals) constraints that can separate food-web dynamics that are possible from those that are not" (Drouineau et al., 2023). CaN modelling can be used where data is missing, as it explicitly accounts for the uncertainty in the model inputs. These model inputs are presented in two different forms, implicit and explicit constraints. The implicit constraints are described as component parameters, showing the parameters of species' inherent characteristics and life history. These parameters are digestibility, assimilation efficiency, other losses, inertia, and satiation. The explicit constraints

are more rigid and can be used to describe the system in a variety of ways. If information about the system is known, or unknown, these explicit constraints can be used to restrict the model. All the constraints together form a set of restriction that separates possible food-web dynamics from impossible ones.

The model provides an output that has multiple possible reconstructions in the form of trajectories of the ecosystem without assigning likelihood or probability to individual trajectories. From these initial outputs, more information can be derived, such as ecological patterns that are necessary to investigate the intrinsic interaction within the ecosystem. These derived patterns may include patterns in the diet fractions of predators and total consumption of prey. These patterns can reveal changes over time in correlation with other changing factors in the ecosystem, potentially displaying an underlying interaction with other trophospecies in the ecosystem. The consumption correlation patterns can be used to look at each trajectory in every year and draw correlations between the consumption by different predator(s) (groups) of a certain prey (group), thus providing a clearer insight in the food-web interactions between marine mammals and the fisheries.

2 Objectives

The objectives of this study are twofold. Firstly, we aim to reconstruct a collection of possible trajectories of the Norwegian and Barents Sea food webs, spanning the last three decades, in compliance with existing data and knowledge. Secondly, we aim to analyse whether the biomass of marine mammals in the Norwegian and Barents Seas was affected by changes in prey biomass driven by fisheries catch and vice versa over the past 35 years. This study will be looking at the correlation between consumption and removal over the entire period using a "Chance and Necessity" modelling approach (CaN, Planque & Mullon, 2020).

3 Materials and methods

3.1 Study area

3.1.1 Hydrography

The Norwegian Sea is a deep sea with an average depth of 1800m. It contains two basins that are deeper than 3000m: the Norwegian Basin in the south and the Lofoten Basin in the north. The Norwegian Sea is adjacent to the Greenland and Iceland Seas, separated from the Greenland Sea by the Mohn Ridge and from the Iceland Sea by the Jan Mayen Ridge (Loeng & Drinkwater, 2007). The Norwegian Sea is characterised by three water masses: Coastal water, Atlantic water, and Arctic water (Figure 1). The coastal water current is a water mass that follows the Norwegian Shelf, east of the Atlantic water. The Atlantic water flows predominantly through the Faroe Island–Shetland channel northward towards the Barents Sea and is relatively warm and saline (Blindheim, 2004). Lastly, the Arctic water, enters the Norwegian sea from the southwest, as a divergent current from the East Greenland Current called the East Icelandic Current.

The Barents Sea is a shallow-shelf sea with an average depth of 230m and is strongly influenced by the bottom topology and the ocean currents (Figure 1). Coming in from the west is the relatively warm Atlantic water (T>2˚C) (Loeng & Drinkwater, 2007), which meets the cold Arctic water (T<0˚C) coming from the north and east (Hunt et al., 2013). These two water masses meet within the Barents Sea ecosystem and create the Polar Front, which is a transition zone between the two water masses (Fossheim et al., 2015; Oziel et al., 2016). Historically, during winter, the edge of the seasonal ice cover was just north of the Polar Front. However, the ice cover has varied both seasonally and inter-annually with a decreasing trend, changing the extent pf the ice in relationship to the Polar Front (Lien et al., 2017; Polyakov et al., 2010).
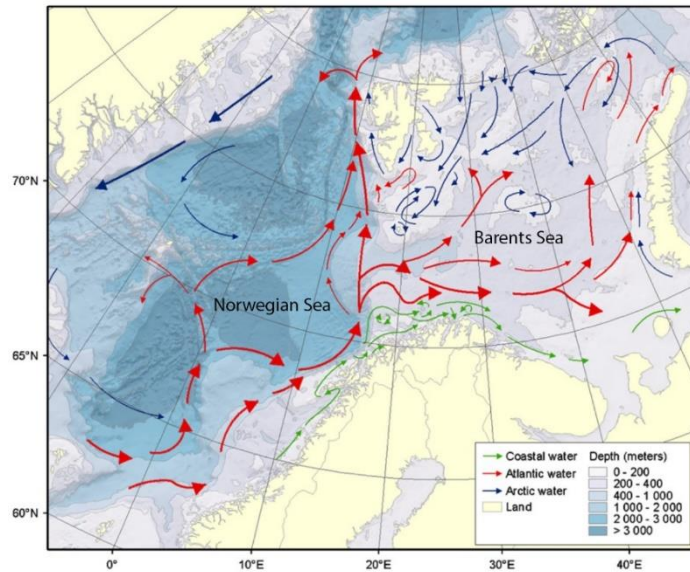
Figure 1. Schematic of the study area and the ocean currents in the Norwegian and Barents Sea. (Loeng & Drinkwater, 2007)

3.1.2   Primary production

The Norwegian sea is a highly productive sea that exhibits protracted spring blooms with annual reported primary production of ca. 80 to 120 gC m^{-2}y^{-1}. (Mignot et al., 2016). During the winter and early spring, the phytoplankton production tends to be low (<20 mg C m^{-2} day^{-1}) and is mostly composed of small flagellates (Loeng & Drinkwater, 2007; Rey, 2004). This is followed by a larger production, mainly composed of diatoms, that begins in March and tends to decrease by summer. This production is mostly a response to increasing light levels and high nitrate concentration. This leads to spring bloom production typically reaching between 200 and 400 mg C m^{-2} day^{-1}(Rey, 2004). As the water becomes more stratified in May, so does the the production, reaching much higher numbers (exceeding 300–500 mg C m^{-2} day^{-1} and reaching 1-1.5 g C m^{-2} day^{-1}) (Loeng & Drinkwater, 2007). In autumn, increased winds cause additional mixing of water masses, which creates small blooms, but towards October, even though nutrients are still increasing, the production is limited by the declining light level.

The Barents Sea contributes significantly to the total primary production of the pan-Arctic shelf. This is owed to the inflow of the different water masses into the region (Wassmann et al., 2006). The Barents Sea serves as a crucial flow-through shelf towards the Arctic Ocean, holding a dominant position in facilitating the movement of water masses – and, therefore, nutrients – through the region (Wassmann et al., 2006). In the Barents sea, phytoplankton blooms appear to be more irregular (Sakshaug, 1997). In early summer, a significant portion of the Barents Sea

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undergoes the process of stratification, accompanied by the onset of the peak of the phytoplankton bloom. The stratification layer formation is primarily attributed to the melting of ice at the northern edge and the inflow of low-salinity water from the Norwegian Coastal Current originating in the southwest. The annual phytoplankton production in the Barents Sea ranges from 20 to 200 g C m^{-2}, with an average value of approximately 90 g C m^{-2}, which is comparable to the mean annual primary production of the Norwegian Sea.

3.1.3   Secondary production

The link between phytoplankton and higher trophic levels is through secondary production. In the Norwegian Sea the most abundant group is the copepods, most notably the *Calanus spp.* They are advected to the Barents Sea ecosystem within which this group also plays an important role: as herbivorous consumers (Melle et al., 2004). In the Norwegian Sea, the general functional groups consist of krill (Euphausiids), zooplankton (Calanoids), and mesopelagic organisms (Cephalopoda and mesopelagic fish). These groups provide a large amount of the biomass that supports higher trophic levels. Krill and the zooplankton are the most abundant groups in the Norwegian Sea. The mesopelagic organisms mostly populate the deep basins and the slopes within the Norwegian Sea ecosystem.

The food-web in the Barents Sea builds on the high primary production, with a variety of different herbivorous and carnivorous functional groups such as copepods, krill, amphipods and benthic fauna (Jakobsen & Ozhigin, 2011). From these, it is mainly the herbivorous amphipods, copepods and krill that link the primary production in the Barents Sea to the higher trophic levels (Falk-Petersen et al., 2000; Pasternak et al., 2001). The fauna in the region is characterized by the largely distinct nature of the Atlantic and Arctic water masses, which host different species depending on their respective abiotic factor regimes. More specifically, the Atlantic water mass is typically inhabited by temperate species, while the Arctic Ocean water mass tends to support more arctic species. The temperate species include *Calanus finmarchicus* (Gunnerus, 1770) and euphausiids. The arctic species include *Calanus hyperboreus* (Krøyer, 1838), *Calanus glacialis* (Jaschnov, 1955), and *Themisto libellula* (Lichtenstein in Mandt, 1822).

3.1.4 Fish

The Norwegian Sea is a vital feeding area for a number of largely exploited fish stocks, including the Norwegian spring spawning herring (*Clupea harengus*, Linnaeus 1758), blue whiting (*Micromesistius poutassou*, Risso 1827), and Northeast Atlantic mackerel (*Scomber scombrus*, Linnaeus 1758). These species rely on the aforementioned groups of zooplankton, krill, and amphipods for sustenance (Bachiller et al., 2016; Langøy et al., 2012; Prokopchuk & Sentyabov, 2006). The mature fraction of the Norwegian spring spawning herring stock spends their time almost exclusively in the Norwegian Sea, the blue whiting stock is believed to spend only 50% of their time in the Norwegian sea, and the Northeast Atlantic mackerel stock between 12,5% (Dommasnes et al., 2001) and more than 50% (Nøttestad et al., 2016). Variations in individual abundance levels of the three pelagic fish populations has been recorded in the Norwegian Sea since the late 1960s. However, starting from the late 1980s, the cumulative abundance of these populations has demonstrated a consistent increase (Dragesund et al., 1997; Huse et al., 2012; ICES, 2022c; Misund et al., 1998).

In the Barents Sea, a lipid-rich zooplankton community attracts large populations of a variety of fish species like Atlantic herring (*Clupea harengus*, Linnaeus 1758), capelin (*Mallotus villosus,* Müller 1776), Atlantic cod (*Gadus morhua,* Linnaeus 1758*)*, polar cod (*Boreogadus saida,* Lepechin 1774), saithe (*Pollachius virens*, Linnaeus 1758), haddock (*Melanogrammus aeglefinus*, Linnaeus 1758), and Greenland halibut (*Reinhardtius hippoglossoides,* Walbaum 1792)(Edvardsen et al., 2003; Eriksen et al., 2021; Ingvaldsen & Gjøsæter, 2013; Kjesbu et al., 2014; Wassmann et al., 2006). The Barents Sea also serves as a spawning area for a variety of different fish species, such as Atlantic herring, capelin, Atlantic cod, and polar cod (Gjøsæter, 1998; Hop & Gjøsæter, 2013). The Norwegian spring spawning herring utilizes the Barents Sea as a nursery habitat. The species deposits their eggs in the waters proximate to Lofoten. After an incubation period of approximately three weeks, the eggs hatch and the newly-hatched larvae are transported via oceanic currents to the Barents Sea (Jakobsen & Ozhigin, 2011; Varpe et al., 2005). The Barents Sea is an important ecosystem for fisheries. Some of the species previously mentioned are a big part of those fisheries, as the commercial fisheries removes on average 1.16 million tonnes year^{-1}, with the highest percentage of catch comprising Atlantic cod and capelin (ICES, 2022b; Skern-Mauritzen et al., 2022a).

3.1.5   Marine Mammals

A total of 22 marine mammal species, both residential and migratory, inhabit the Norwegian and Barents Seas, including seven pinnipeds, six mysticetes, and nine odontocetes. More than half (14) of these species are resident species whereas eight are seasonal migrants that exploit these highly productive ecosystem during spring, summer and autumn (Skern-Mauritzen et al., 2022a). Some of the resident species – harp seal, hooded seal, and bowhead whales – perform seasonal migrations within or between the Norwegian and Barents seas (Folkow et al., 2004; Lydersen et al., 2012; Nordøy et al., 2008; Vacquie-Garcia et al., 2017). These marine mammals are attracted to the Norwegian and Barents Seas because of the large fish stocks and high secondary production. Marine mammals in the Norwegian and Barents Seas are reported to have, respectively, a 3.1 and 6.1 times higher average annual consumption compared to the fisheries annual catch (Skern-Mauritzen et al., 2022a).

In this study, minke whale (*Balaenoptera acutorostrata,* Lacépède 1804) is treated separately from of its functional group – the mysticetes – as the minke whale plays a key role within the ecosystem as a consumer and as a species targeted by hunting over the past decades (Corkeron, 2009; Haug et al., 1995; NAMMCO, 2022). The minke whale is not the only species that is actively hunted within the Norwegian and Barents Sea. Other species include harp seal, hooded seal, grey seal, ringed seal, and bearded seal (NAMMCO, 2022).

3.1.6   Birds

The Norwegian and Barents Sea are foraging grounds for several bird species, that feed primarily on the pelagic fish stocks. The birds include 17 species that use the Norwegian and/or the Barents Sea. Some species include northern fulmar (*Fulmarus glacialis*, Linnaeus 1761), common guillemot (*uria aalge,* Pontoppidan 1763), and Atlantic puffin (*Fratercula arctica*, Linnaeus 1758). For a full list of species for all components see Appendix 2 – Species list**.**.

3.2 Adjacent waters

Adjacent to the Norwegian Sea lie the Greenland and Iceland Seas, which hold significance for the pelagic fish species present in the Norwegian Sea. Among these species, mackerel and blue whiting are widely distributed and are known to spend a considerable portion of their time in these waters (Bailey, 1982; Nøttestad et al., 2016). These species utilize the Norwegian Sea as

a feeding ground, with recent studies indicating an increase in their distribution towards the north and west (Bachiller et al., 2016; Nøttestad et al., 2016).

3.3 The Norwegian Sea and Barents Sea CaN model

The Norwegian and Barents Sea model was constructed in collaboration with selected specialists in the Norwegian Sea and Barents Sea ecosystems working at the Institute of Marine Research (IMR) and the Arctic University of Norway (UiT). A workshop in January 2022 was organised to produce a representation of the Norwegian and Barents Seas ecosystems as a food web model. This workshop was used to discuss how to accurately represent the food-web structure in the Norwegian and Barents Sea ecosystems, while simultaneously limiting the complexity of the model and enabling it to answer the research question. Another workshop was held in April 2023 to elaborate the results and have experts in their respective fields look at the model output.

A standard "Overview, Design concepts, and Details" (ODD) model description protocol (Grimm et al., 2006, 2010, 2020) was followed to provide a detailed description of the CaN model for the Norwegian Sea and Barents Sea food-web. This work will closely follow the model by Planque, Favreau, et al. (2022)

3.3.1 Purpose and patterns

The CaN framework is a tool for modelling the dynamics of food webs. Its primary objective is to reconstruct the potential trajectories of a given food-web based on available knowledge and observations of the past dynamics of said food-web (Drouineau et al., 2023). The objective is to evaluate whether the biomass of marine mammals in the Norwegian and Barents Seas was affected by changes in prey biomass driven by fisheries catch and vice versa over the past decades. The model produces a set of trajectories that can be used to create an analysis of the emergent ecological patterns. The primary ecological patterns are the interannual fluctuations in biomass and fluxes of the groups represented within the model domain (Table 1). Other ecological patterns can be analysed as pertaining to the objective. These patterns include average diet composition, correlation of prey availability to prey removal, and emerging trophic functional relationships.

3.3.2   Entities, state variables and scales

Within the CaN, food-webs are specified by components, the species or functional groups, and fluxes between the components. These fluxes can be trophic (feeding interaction) or non-trophic (fisheries catch). The model covers the period of 1988 until 2021 and has an annual time step, where the state variables are the biomass of the components at each time step. Within the domain of our model there are twelve components. These components' biomasses are dynamically modelled. These components are divided into two group, a Norwegian Sea and a Barents Sea group. The Norwegian Sea group components are adult Norwegian spring spawning herring, blue whiting, and Atlantic mackerel. The Barents Sea components are Atlantic cod, polar cod, juvenile Norwegian spring spawning herring, other demersal fish, and capelin. Four of the twelve components cover both areas: these are minke whale, other baleen whales, toothed whales, and seals. Outside of the bounds of the model are fourteen components which are not dynamically modelled but contribute to the transfer of biomass in and out of the model domain. In short, throughout all the model trajectories, the fluxes and components within the model domain are followed. However, for groups outside the model domain, only the fluxes are considered and dynamically modelled. These external components are, similarly to those within the model domain, split geographically. The external Norwegian Sea components are krill, zooplankton, and mesopelagic and other fish. The external Barents Sea components are krill, copepods, amphipods, and benthic fauna. There are six further external components which cover both areas and those are the outside resources, outside predators, pelagic fisheries, demersal fisheries, marine mammal fisheries, and birds.

Table 1. Component list of trophospecies within the model domain with all the represented species in each component. NS stands for Norwegian Sea and BS for Barents Sea. Where neither is mentioned, the component is present in both systems.

Component	Species
HerringNS	Norwegian spring spawning herring – Adult
BlueWhitingNS	Blue whiting
MackerelNS	Atlantic mackerel
CodBS	Northeast Arctic cod
PolarCodBS	Polar cod
HerringBS	Norwegian spring spawning herring – Juvenile
CapelinBS	Capelin
OtherDemersalBS	Saithe, haddock, long rough dab, Greenland halibut, golden redfish
MinkeWhale	Common minke whale
ToothedWhales	Sperm whale, killer whale, harbour porpoise, white sided dolphin, white beaked dolphin, narwhale, beluga whale, long-finned pilot whale, northern bottlenose whale
OtherBaleenWhales	Fin whale, blue whale, bowhead whale, sei whale, humpback whale
Seals	Hooded seal, harp seal, ringed seal, grey seal, harbour seal, bearded seal, walrus

The model is not spatially bounded. This entails that the geographic boundaries are set to the Norwegian and Barents Seas, but the species within can display larger stocks that extend beyond these boundaries. Blue whiting and mackerel stocks are considered inside the model and spend a considerable amount of time outside of the Norwegian Sea. A similar approach is used for the marine mammals. To accompany this these trophospecies there are fluxes that connect them to outside resources and outside predation. Furthermore, due to the life history of capelin, a non-trophic link to the benthos has been introduced to account for their spawning mortality.
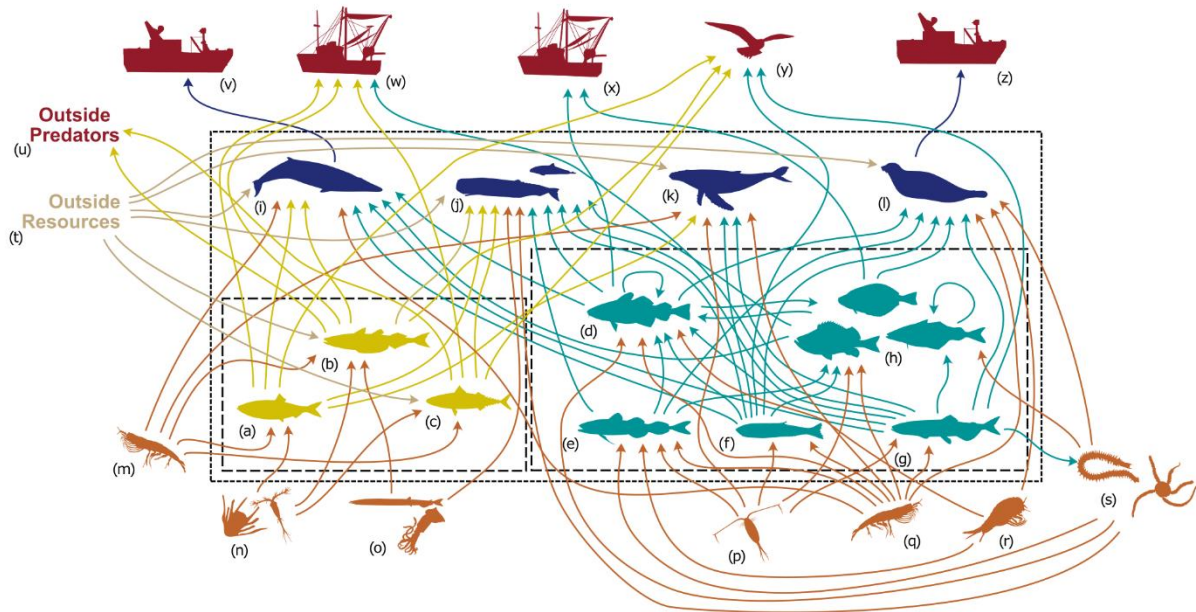
Figure 2. Conceptual model of the Norwegian and Barents Sea CaN model. (a) Norwegian spring spawning herring, (b) blue whiting, (c) Atlantic mackerel, (d) Atlantic cod, (e) polar cod, (f) juvenile Norwegian spring spawning herring, (g) capelin, (h) other demersal fish, (i) minke whales, (j) toothed whales, (k) other baleen whales, (l) seals, (m) Norwegian Sea krill, (n) Norwegian Sea zooplankton, (o) Mesopelagic and other fish, (p) Barents Sea copepods, (q) Barents Sea krill, (r) Barents Sea amphipods, (s) Barents Sea benthic fauna, (t) resources outside of the Norwegian and Barents Sea, (u) predators outside of the Norwegian and Barents Sea, (v) minke whale hunting, (w) pelagic fisheries, (x) demersal fisheries, (y) birds, and (z) seal hunting. The model domain is shown as the outermost dashed rectangle. The two inner dashed rectangles represent the species groups in either the Norwegian Sea (yellow) or the Barents Sea (teal). The arrows symbolise trophic and non-trophic links and are coloured according to the prey group. This figure does not distinguish between trophic and non-trophic links.

3.3.3 Process overview and scheduling

The CaN model reconstructs the dynamics of species biomass within an ecosystem. The model uses a discrete time framework where the biomass at a given point in time $(t + 1)$ is solely determined by the biomass at the previous time point (t) and the fluxes that occurred during that interval. Specifically, the model relies on a balance between incoming fluxes (i.e., consumption or import) and outgoing fluxes (i.e., predation, export, or fisheries) to reconstruct the dynamics of biomass. While the model is deterministic in terms of biomass calculations, the fluxes between components are stochastic and are drawn randomly from a range of possible values that adhere to pre-established constraints. This stochastic aspect of the model enables the inclusion of chance events and variability in the simulation.

3.3.4 Design concepts

The ODD includes sub-questions within the design concepts. However, the questions about adaptation, objectives, learning, prediction, sensing, and interaction, and collectives were not used, as they are not relevant for CaN models.

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3.3.4.1 Basic principles

CaN model is much like Ecopath, a mass balance modelling approach, where the in- and outflow of the components are modelled. CaN is a modelling approach that uses linear inverse modelling (LIM), based on "Chance and Necessity" modelling. Unlike the approach used in Ecopath, CaN modelling is not static and at equilibrium. CaN models account for "Chance, i.e. the stochasticity of nature and for Necessity, i.e., the existence of physical (e.g. mass conservation) or ecological (e.g. inertia of populations, satiation of individuals) constraints that can separate food-web dynamics that are possible from those that are not" (Drouineau et al., 2023). In further comparison to Ecopath, the master equation is slightly different (Appendix 1 in (Planque et al., 2014).

3.3.4.2 Emergence

The output of CaN models are time-series of all the fluxes and the biomasses of modelled species at each time-step. These raw outputs can be used to derive emergent properties, such as diet fractions for the individual components, their total consumption, trophic level of the components, and consumption correlation between components. In this study, the focus is on two emergent properties. The first is the diet composition to analyse dietary overlap between marine mammals and the fisheries. The second relevant emergent property is the consumption correlation between components. This can indicate the type of interaction present between the components. Highlighting potential resource competitions, bottom-up, or top-down effects between components. Bottom-up and top-down effects entail the presence of either a resource or predator driven trophic control, respectively. This means that for a bottom-up effect "a lower trophic level in the biological network affects the community structure of higher trophic levels by means of resource restriction" (Carpenter et al., 1985). A top-down effect "refers to a higher trophic level influences the community structure of a lower trophic level through predation" (White, 1978).

3.3.4.3 Stochasticity

As previously mentioned, CaN models are stochastic, as the fluxes between components are stochastic and drawn at random from a range of possible values that adhere to pre-established constraints. Therefore, it is possible for the CaN model to draw many random food-web trajectories within the given constraints. Each individual food-web trajectory has no probability associated with it, thus making CaN models possibilistic.

3.3.4.4   Observation

The CaN model produce stochastic biomass trajectories of ecosystem components and the biomass flux between components. Based on these properties, several other ecosystem properties, such as diet fractions, functional response relationships, density dependence, ecosystem stability etc, can be derived (see Lindstrøm et al. 2017). In this study, the following properties were reported derived:

1. Time-series of components' biomasses and the fluxes between them
2. Diet composition
3. Correlation between biomasses and fluxes

Each CaN model sample is comprised of a set number of trajectories. These trajectories are all possible trajectories within the constraints. These are all used to explore the distribution of all the trajectories generated.

3.3.5   Initialisation

The initial state of the model is necessary to accurately address as it is critical for replication purposes. The start year of the model is 1988 and the initial biomass of the components within the model are not specified as this is not needed. The model samples the first set of biomasses during the modelling phase.

The initial modelling elements within the Norwegian and Barents Sea CaN model are:

- The list of components and the fluxes between them (Figure 2 & Appendix 2 – Species list)
- The components' specific input parameters that are used in the CaN master equation and are used to define implicit model constraints (Model input parameters)
- A list of input data based on observations, such as survey data, model outputs. This often comes in the form of a data-series.
- The list of explicit constraints (Appendix 4 – Constraints documentation).

3.3.6   Input data

The model can be constrained by data in the form of time-series. These time-series can have different origins, such as field measurements, surveys, and modelling outputs from other publications. Surveys play a significant role within the model as many time-series for the

Norwegian and Barents Seas are gathered and reported on annually by, for example the International Council for the Exploration of the Sea (ICES). Another form of time-series data is diet data for cod, herring, blue whiting and mackerel, as data has been gathered through stomach-sampling programs (Eriksen et al., 2020; Howell et al., 2022; Langøy et al., 2012; Planque et al., 2014). Information regarding the total annual consumption of herring, blue whiting and mackerel are taken from bioenergetics model results (Bachiller et al., 2018).

3.3.7 Model constraints

The model is constructed with the use of constraints, which are specific to CaN. Constraints are linear equalities/inequalities that specify the range/flow that is deemed possible or impossible. This is used to express the expert knowledge that we have about the ecosystem as a written and explicit constraint. The constraints are written in the form of a symbolic expression, that can use the model inputs (time-series), components, and fluxes within the expression to accurately represent the expert knowledge within the model. All CaN models inherently incorporate implicit or compulsory constraints that reflect certain ecological realities. These constraints include ensuring that biomasses and fluxes are always positive, bounding the growth and mortality rates of trophospecies (also known as the inertia constraint), and bounding the maximum feeding rate per unit of time or biomass (also known as the satiation constraint). For example, many ICES working groups have annual fish stock biomass assessments which are presented with a mean and 95% confidence interval (CI). This 95% CI can be used as an upper and lower boundary of the total stock biomass for each year, using a constraint.

To illustrate how these constraints are build and written, here is a short explanation. It starts with finding a good reference that contains knowledge about the system. This can be used to narrow (constrain) the model. This knowledge can present itself in a variety of ways, ranging from biomass time-series, singular or multiple observations, or an educated assumption based on expert knowledge. This data is sometimes given with an uncertainty. This uncertainty can directly be implemented as a single constraint (Equation 4**Error! Reference source not found.**) or as a multiple constraints bordering the data point (Equation 3). This directly shows the flexibility and specificity of the model constraints. Here are some more examples of constraints that have different origins as well as their own uncertainty or lack there off. In this scenario, an assumed uncertainty is used (Equation 3) or no uncertainty is necessary (Equation 1).

$$CodBS\_FDemersal = FisheryCod$$

Equation 1. An example constraint showing the biomass of cod in the Barents Sea that is taken by the fisheries. CodBS_FDemersal equals the flux from the cod biomass to the fisheries and the FisheryCod is a table with total catch biomass of cod for each year.

$$CodBS <= CodObsHigh$$

$$CodBS >= CodObsLow$$

Equation 2. An example constraint showing the upper and lower bounds of the biomass for Cod in the Barents Sea. Where CodBS equals the biomass of cod at time t and the CodObsHigh/Low are time-series of the upper and lower bounds for the biomass of cod in the Barents Sea.

$$mean(MinkeWhale[1996:2001]) * ones <= 546 * 1.2$$

$$mean(MinkeWhale[1996:2001]) * ones >= 546/1.2$$

Equation 3. Two example constraints showing the mean upper and lower limit of minke whale for the period of 1996 until 2001. That is, this constraint is active from the year 1996 until 2001 constraining the mean biomass of minke whale over that period and giving it a mean upper limit. The mean over that time-period cannot exceed the stated value.

$$CapelinBS\_CodBS/(InflowsCodBS) <= 0.84$$

Equation 4. An example constraint showing the maximum fraction of cods' diet that con consist of capelin.

Box 1. In-depth look at the construction and layout of the constraints in the model. These constraints are picked from the model to display the complexity and versatility of the constraints.

There are different types of constraints active in the Norwegian and Barents Sea CaN model. For example, there are constraints that operate on a component's biomass so as to indirectly restrict the fluxes from that component to others. Other constraints are flux constraints which indirectly restrict the biomass of both predator and prey components. In addition to these constraints there are the implicit constraints, these are constraints that are specific to each component. These are known as the first principle constraints and constrain the components based on life history and metabolic theory of ecology (Lindstrøm et al., 2017). Satiation (σ), inertia (α), other losses (μ), assimilation (γ), and digestibility (κ) are the implicit constraints. Satiation constrains the total amount of inflow to the component, as it gives the maximum amount of consumption in reference to the component's body weight. Inertia limits the maximum interannual fluctuation. Other losses correspond to the mortality coefficient that includes metabolic losses and other losses that are not explicitly expressed in the model. Assimilation is the efficiency of the predator in taking up the biomass of the ingested prey. Lastly, digestibility is a correction that accounts for the variety of prey's energy content. These biological parameters are necessary for restricting the components within the model domain. For the components outside the domain, only one parameter – digestibility – is necessary if the component is a prey species. More information on these implicit constraints is provided in Model input parameters .

Finally, the constraints exhibit a considerable degree of temporal variability. Specifically, certain constraints, such as the implicit ones, persist throughout the entire duration of the model. In contrast, other constraints are imposed only for a restricted interval of time, thereby limiting their application to the period within which the observation or measurement is relevant. This temporal variability enables the constraints to be selectively applied in a manner that aligns with the specific temporal context of the measurement/observation.

3.3.8   Submodels

Chance and Necessity (CaN) models exhibit a simplistic framework comprised of the CaN master equation (Equation 5), The series of constraints, time-series, and meta-information. These models are specifically designed to account for the dynamics of biological systems and their responses to various environmental factors. The CaN master equation plays a pivotal role in tracking the changes in biomass over time within the different components of the model and the consequent biomass fluxes between them. It is noteworthy that CaN models are explicitly

formulated to capture the interplay between chance events and deterministic mechanisms, thus providing a comprehensive understanding of the underlying biological phenomena.

$$B_{i,t+1} = e^{(-\mu_i)} B_{i,t} + \frac{(1 - e^{(-\mu_i)})}{\mu_i} \left[\gamma_i \sum_j \kappa_j F_{ji,t} - \sum_j F_{ij,t} \right] \qquad \text{Equation 5}$$

The master equation in the CaN model. Bi, t is the biomass of the component i at time t. μ, γ, and κ are the internal input parameters. μ represents other losses, γ is assimilation efficiency, and κ is digestibility. F$_{ij}$ and F$_{ji}$ are the biomass fluxes between components i and j.

The master equation is not easily comprehensible without some explanation, so let's look at each term individually.

First, the term before the equals, $B_{i,t+1}$, and $B_{i,t}$, are similar. They both express the biomass of the component itself, here represented as i, at time t. However, the $B_{i,t+1}$ is slightly different as it shows the biomass at time $t + 1$, indicating the next time-step.

Second, μ_i, represents the other losses for component i. Other losses accounts for the mortality coefficient: that is, metabolic losses and other mortality that is not explicitly accounted for in the model. This term is made strictly positive and is used with the biomass at time t.

Third, the term $\frac{(1 - e^{(-\mu_i)})}{\mu_i}$, is used to integrate the time-step into the equation.

Fourth, γ_i. This term is used within the boundary of $\left[\gamma_i \sum_j \kappa_j F_{ji,t} - \sum_j F_{ij,t} \right]$, which defines the total inflow and outflow of the component. This term, γ_i , defines the assimilation efficiency of the component. All the inflow into the component is multiplied by the efficiency of the component's biomass uptake.

Fifth, κ_j. This term is again related to the total inflow and outflow of the component. However, its is only present on the inflow and is specific to j. Thus, ji represents another component that i is consuming. This term, κ_j, stand for the digestibility of the prey j. Lastly, $F_{ji,t}$ and $F_{ij,t}$. These two terms represent the in- and outflow. The order of the elements ji or as ij shows the direction of the flow.

$$B_{i,t+1} = e^{(-\mu_i)} B_{i,t} + \frac{(1 - e^{(-\mu_i)})}{\mu_i} \left[\gamma_i \sum_j \kappa_j F_{ji,t} - \sum_j F_{ij,t} \right]$$

Biomass at time t+1 — Other losses — Biomass at time t — Time-step integration — Assimilation efficiency — Digestibility — Inflows — Outflows
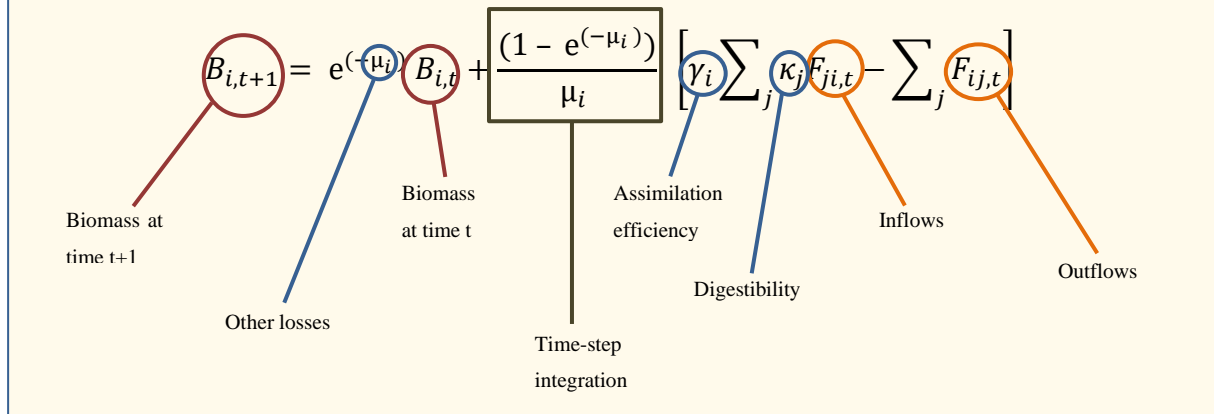
Box 2, In-depth look at the master equation used in the CaN model. This explains individual terms of the equation and provides a better understanding of the master equation.

3.3.9 Model input parameters

The model input parameters are derived from life history theory, metabolic theory of ecology (Savage et al., 2004a), allometric relationships (Gillooly et al., 2001; Makarieva et al., 2008; R. J. Williams et al., 2007; T. M. Williams et al., 2004; Yodzis & Innes, 1992), direct measurements (Johnstone et al., 1993), or adapted from models (Pedersen et al., 2021; Planque, Favreau, et al., 2022).

Table 2. The input parameters of each component within the model domain (as calculated using the equations and methods described in Model input parameters).

Species	Potential assimilation efficiency	Digestibility correction factor	Satiation	Inertia	Other losses
HerringNS	0.9	0.9	12	0.64	2.28
BlueWhitingNS	0.9	0.9	9	0.85	2.8
MackerelNS	0.9	0.9	12	0.63	2.26
CodBS	0.8	0.9	3	0.28	1.14

PolarCodBS	0.8	0.9	8	1.21	3.2
HerringBS	0.84	0.9	7.9	0.85	2.55
CapelinBS	0.8	0.9	9.3	1.6	2.55
OtherDemersalBS	0.8	0.9	3.2	0.37	1.43
MinkeWhale	0.92	0	11.95	0.2	7.2
ToothedWhales	0.925	0	8.62	0.15	5.24
OtherBaleenWhales	0.92	0	7.22	0.12	4.37
Seals	0.885	0	30.66	0.18	17.59

3.3.9.1 Potential assimilation efficiency

The potential assimilation efficiency, γ, corresponds to the proportion of ingested prey biomass that is effectively assimilated by the predator. The value of this parameter ranges between 0 (indicating no assimilation) and 1 (complete assimilation). The parameter values employed for the species included in this study were obtained from (Bachiller et al., 2018; Brett & Groves, 1979; Hop et al., 1997; Pedersen et al., 2021; Planque, Favreau, et al., 2022) and are presented in Table 2.

3.3.9.2 Digestibility correction factor

The digestibility correction factor, κ_j, accounts for the variations in energy content and digestibility of prey. The value of this parameter ranges between 0 (no energy content) and 1 (high energy content). The parameter values employed for the species included in this study were obtained from Lindstrøm et al. (2017) and Planque, Favreau, et al. (2022).

3.3.9.3 Satiation

Satiation, σ (kg prey·kg predator^{-1}), is the maximum consumption per unit biomass of a predator per unit time. A value of, for example, 3 indicates that the predator can eat 3 times their own biomass in prey biomass. The parameter values employed for the species included in this study were obtained from general theoretical formula from Yodzis & Innes (1992). More information can be found in Appendix 3 – input parameters calculations.

$$\sigma_j = \frac{1}{\gamma_i \kappa_j} f_J a_J M_j^{-0.25}$$

Equation 6

The satiation equation from Yodzis & Innes (1992). γ_i represents the potential assimilation efficiency, κ_j represents the digestibility correlation factor, f_J fraction from is an ecosystem specific fractional quantity, a_J (kg·(kg·y-1)·kg0.25) is the coefficient of the allometric relationship between the maximum rate of metabolizable energy and the weight of the species, and M_j is the average individual weight of the predator species (kg).

3.3.9.4 Inertia

Inertia, α (y^{-1}), is the maximum change of biomass a component can have over a unit of time. Inertia is strictly positive and is given by e^{α}. With a given inertia of 1, the maximum rate of change is limited to e^1 (2.71) and e^{-1} (0.37), meaning a maximum change of 271% and 37% from the initial biomass (at time t). The inertia for each component was derived from allometric relationships (Savage et al., 2004a; R. J. Williams et al., 2007; Yodzis & Innes, 1992).

3.3.9.4.1   Yodzis & Innes (1992)

In Yodzis & Innes (1992) an equation to estimate the species' maximum growth rate (ρ_i) is suggested:

$$\rho_i = f_r a_r M_i^{-0,25}$$

Equation 7

The maximum species growth rate by Yodzis & Innes (1992), where M_i is the average individual weight (kg) of the species i. f_r is the fractional quantity and α_r is the coefficient of the allometric relationship between the maximum rate of metabolisable energy and the weight of the species.

Changes to the parameter values for Equation 7 were made by R. J. Williams et al. (2007).

3.3.9.4.2   Savage et al. (2004)

Savage et al. (2004) suggested the daily maximum growth rate (r_{max}) as follows:

$$r_{max,i} = e^{a_{s,i}} e^{\frac{-b_{s,i}}{kT_i}} M_i^{-0.25}$$

<div align="right">Equation 8</div>

The daily maximum species growth rate by Savage et al. (2004), where M_i is the average individual weight (µg) of the species i. a_s and b_s are the species-specific coefficients. k is the Boltzmann constant, and T_i is the body temperature of the species i in Kelvin.

This daily maximum growth rate is converted into the correct time step by multiplying it by the residence time in days year^{-1}.

The trophospecies' inertia in the model is calculated by taking the arithmetic mean ($\overline{\alpha}$) of maximum growth rates for each species from each method of calculation.

3.3.9.5 Other losses

Other losses, µ (y^{-1}), is the mortality coefficient that accounts for losses. It is assumed to be equal to the field metabolic rate (FMR) of a species, which is estimated at three times the basal metabolic rate (BMR) (Speakman & Selman, 2003). They are expressed as $e^{-\mu}$, making the term strictly positive. In practice, the other losses indicate that with a value of 1, e^{-1}, that after one time unit the biomass is 36% of the initial biomass, equivalent to 0.27% daily loss.

Species' other losses are calculated using two different calculations, applied to all the components and two further calculations applied to only one set. Overall, each component's other losses parameter is derived from three separate equations.

3.3.9.5.1 *Yodzis & Innes (1992)*

Yodzis & Innes (1992) they suggest the following estimation equation for FMR.

$$\mu_i = a_T M_i^{-0,25}$$

<div align="right">Equation 9</div>

The field metabolic rate by Yodzis & Innes (1992), where M_i is the average individual weight (kg) of the species i, and a_T (kg(kg year^{-1})kg$^{0.25}$) a constant that is animal-group specific.

3.3.9.5.2 Gillooly et al. (2001)

Lindstrøm et al. (2017) calculate a FMR in Joule min^{-1} using the following equation from Gillooly et al. (2001), who suggests a daily FMR (Equation 10). The species FMR can be converted to kg kg^{-1} year^{-1} using Equation 11.

$$\mu_i = 3\left(e^{a_{bmr}}e^{\frac{-b_{bmr}\cdot 1000}{T}}M_i{}^{0,75}\right) \hspace{3cm} \text{Equation 10}$$

The daily field metabolic rate by Lindstrøm et al. (2017) adapted from Gillooly et al. (2001), where M_i is the average individual weight (g) of the species i, a_{bmr} and b_{bmr} are taxa specific constants taken from Gillooly et al. (2001), and T is the body temperature of the species i (in Kelvin).

$$FMR_k = \frac{FMR_J \cdot 1440 \cdot d_i}{7 \cdot 10^6 \cdot M_i} \hspace{3cm} \text{Equation 11}$$

Conversion from daily field metabolic rate in Joule min^{-1} to kg kg^{-1} year^{-1}. M_i is the average individual weight (kg) of the species i, FMR_j is the field metabolic rate in Joule min^{-1}, and d_i is the corresponding growth period of the species i. 1440 is the number of minutes during the day with the $7 \cdot 10^6$ corresponding to the assumption that 1kg of wet mass is $7 \cdot 10^6$ Joule (Peters, 1983)

3.3.9.5.3 Makarieva et al. (2008)

The third method by Makarieva et al. (2008) describes the average metabolic rates (AMR$_{MAK}$, W·kg^{-1}) of numerous species and taxa. This method was used only to calculate the FMR for the fish species within the model, as demonstrated below.

$$\mu_i = \frac{AMR_{MAK} \cdot 86400 \cdot d_i}{7 \cdot 10^6} \hspace{3cm} \text{Equation 12}$$

The average metabolic rate (AMR) by Makarieva et al. (2008), where AMR$_{MAK}$ is the species AMR derived by Makarieva et al., (2008) expressed in Joule s^{-1} kg^{-1}. With this equation that rate is converted to kg kg^{-1} year^{-1} using 86400 describing the number of seconds in a day and

d_i the number of days species i grows during a year. $7 \cdot 10^6$ corresponds to the conversion of Joule to wet mass, where 1kg of wet mass corresponds to $7 \cdot 10^6$ Joule (Peters, 1983).

3.3.9.5.4   *T. M. Williams et al. (2004)*

The last method is only used for the other losses of the marine mammal groups. This method is proposed by T. M. Williams et al. (2004) and describes a FMR in Joule per second using the following equation.

$$FMR_b = 19.65M_b^{0.756}$$ Equation 13

The field metabolic rate by T. M. Williams et al. (2004), where the M_b is the species individual body weight in kilograms.

This FMR in Joule per second was afterwards converted to kg kg^{-1} year^{-1} using Equation 12. The arithmetic mean ($\bar{\mu}$) of the estimates was calculated for all components. For more information and details on the derivation and calculation of the input parameters see Appendix 3 – input parameters calculations and Lindstrøm et al. (2017).

The present study employed a Gibbs polytope sampling algorithm, which has been demonstrated to be effective for high-dimensional problems (Drouineau et al., 2021; Laddha & Vempala, 2020). Specifically, 9984 trajectories were generated and thinned at a rate of 1:100 using a standard thinning technique to prevent autocorrelation between Markov Chain Monte Carlo (MCMC) samples. The set of 9984 trajectories was subsequently analysed to investigate the characteristics of past food-web trajectories.

3.3.10   Summary

The Norwegian and Barents Seas CaN model is a food-web model that includes twelve components inside the model domain and fourteen outside of it. The model has a total of 87 fluxes, where 78 are trophic and 9 are non-trophic. Connecting these components and fluxes is the master equation, with the use of the constraints and parameters. There are 256 explicit constraints in addition to the six component-specific implicit constraints. And there are 43 data series from observational/model output data. The constraints can be found in Appendix 4 – Constraints documentation.

The steps for the implementation of CaN models taken from Planque, Favreau, et al. (2022) applied here and include (I) model design (defining the components and the fluxes), (II) entry of input parameters, (III) provision of observational data, (IV) definition of explicit constraints, (V) construction of the system of in/equalities that defines possible trajectories, (VI) sampling possible trajectories and (VII) graphical representation and analysis of the model results..

3.4 RCaN constructor and model simulation

The model was created with the help of the RCaN constructor, a Java graphical user interface that allows the user to create the food-web, set input parameters, set constraints, and track changes (Drouineau et al., 2021, available from https://github.com/inrae/RCaNmodel). The model simulation was simulated using the R package RCaNmodel and run on R using R studio (Posit team, 2023; R Core Team, 2023). Other R packages include; ggplot2 and tidyverse (Wickham, 2016; Wickham et al., 2019).

3.5 Analysis of CaN model output

The initial CaN model outputs are the generated temporal trajectories of the biomass in the model domain and all the fluxes. These outputs serve as an initial evaluation of the dynamics of the food-web. These temporal trajectories consist of possible trajectories, which in unison can display the uncertainty surrounding the biomass in time and the fluxes. From these trajectories it is possible to derive additional outputs and potential patterns that are necessary to investigate the food-web and its mediated interactions. The derived patterns include those of diet fraction, total consumption of individual trophospecies, and consumption over biomass. The diet fraction of each trophospecies is acquired by averaging all the fluxes from each prey to the predator across all the years and trajectories. Another result is the average total consumption per prey of each trophospecies across all years and trajectories. This result can be generated by summing of all the fluxes from each prey to the predator across the years and trajectories.

The patterns that can provide evidence for food-web mediated interactions are consumption correlation patterns, through correlation of the trajectories using Pearson's correlation coefficient. This derives the correlation between the consumption of a specific prey between predators or predator groups. This makes it possible to look at each trajectory in every year and correlate between the consumption of a certain prey (group) by different predator(s) (groups). To do so, we sum the ingoing fluxes of a prey for different trophospecies. In turn, we can

investigate competition between predators by comparing the relationship of their consumption. more in-depth explanation is given in Box 3 about the consumption correlation pattern.

The consumption correlation pattern is derived using the Pearson's correlation coefficient. The Pearson correlation coefficient is a statistical measure that quantifies the degree of linear association between two continuous variables. It is a value between -1 and 1, where -1 indicates a perfect negative linear correlation, 0 indicates no linear correlation, and 1 indicates a perfect positive linear correlation. The coefficient is calculated by dividing the covariance of the two variables by the product of their standard deviations. It determines the strength and direction of the relationship between two variables.

The Pearson's correlation coefficient is useful in assessing the food-web mediated effect., as it shows when two predators, who consume the same prey, are competing for this same resource or if they both can consume their share when abundance of the prey is high.
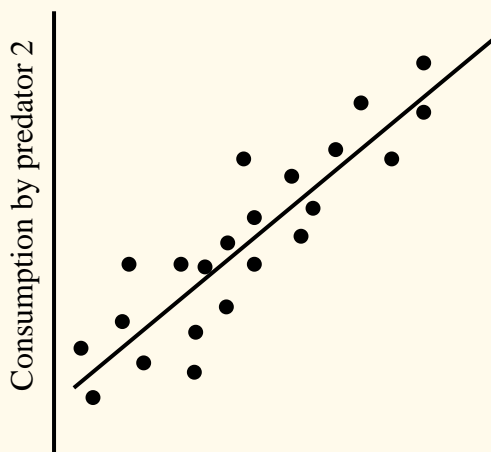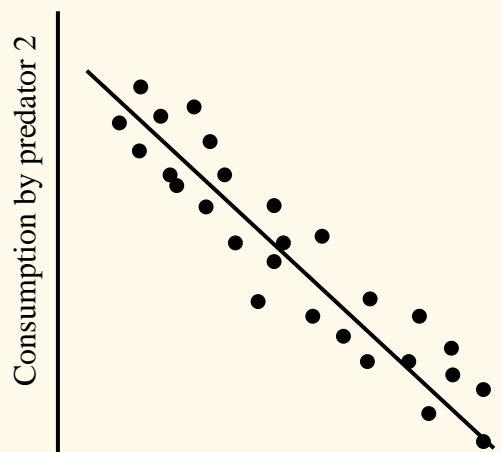
Positive correlation   Negative correlation

Here it is shown that, in a positive correlation, there is a simultaneous increase of consumption by both predators of a prey. The negative correlation shows the increase of consumption by predator 1, correlating with the decrease of consumption by predator 2.

Here it is shown that, in a positive correlation, there is a simultaneous increase of consumption by both predators of a prey. The negative correlation shows the increase of consumption by predator 1, correlating with the decrease of consumption by predator 2. An example table of the correlation coefficient is presented below, with explanations on each part.

Prey species

The comparing predator(s) (groups)

Category	Species	Biomass	Inflow	Correlation
Prey	Blue whiting	3606	NaN	
Predator 1	Minke whale & Toothed whales	1242	735	0.17 [-0.03, 0.37]
Predator 2	Pelagic fisheries	0	1098	

Species represented within the categories

Average biomass of the group (in thousand tonnes

Average consumption of the group of the prey species (in thousand tonnes

Correlation factor R with 95% confidence interval

Each boxplot is a different correlation relationship between two predators/predator groups. When the correlation is positive the interaction is bottom-up controlled, and the shared prey dictates the flow to the predators. When the correlation is negative the interaction between the predators is competitive. The median of the correlation is shown as the solid black line within each boxplot.
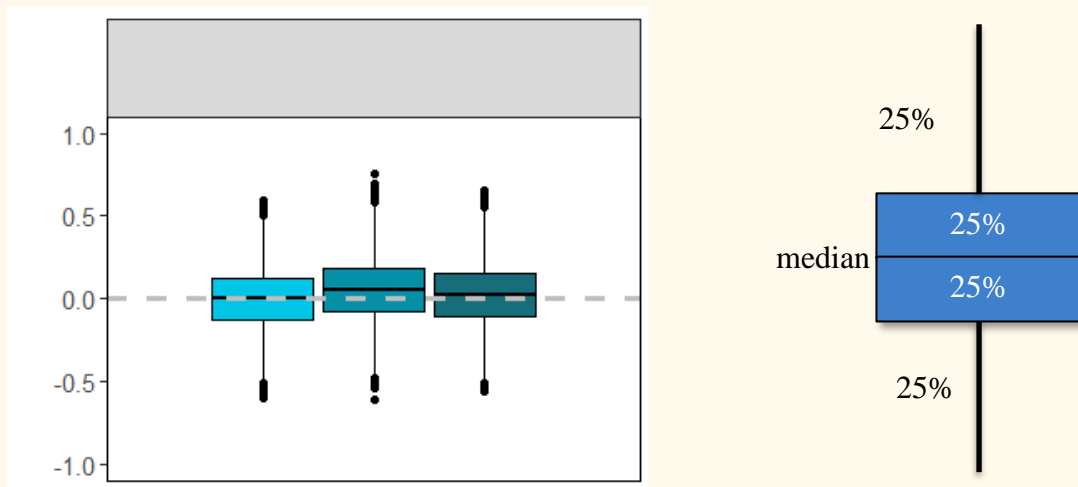
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Each boxplot is a different correlation relationship between two predators/predator groups. When the correlation is positive the interaction is bottom-up controlled, and the shared prey dictates the flow to the predators. When the correlation is negative the interaction between the predators is competitive. The correlation is shown as the solid black line within each boxplot.

Box 3, In-depth look into the consumption correlation pattern used to investigate the presence of negative or positive correlation of prey between predators.

3.5.1 Direct and food-web mediated interactions

Direct and food-web mediated interactions are not measured with a predefined measurement within the ecosystem. In our study, we define direct interactions as the correlation between the consumption by marine mammals and the fisheries catch. This can be in relation to a single shared resource or a group of shared resources.

The food-web mediated interactions are defined in our study as the correlation between the consumption by marine mammals and the consumption by other predators of a single shared resource or a group of shared resources. The correlation can indicate a potential competition between the predators. Whether this may affect the fisheries through the food-web can be discussed.

In cases where the correlation between the consumption of two predators is positive, it signifies that an increase in the consumption of one prey species by predator 1 corresponds to a concurrent increase in the consumption of the same prey species by predator 2, over the last 35 years. A negative correlation indicates the opposite, with an increase in the consumption of one prey species by predator 1 corresponding to a concurrent decrease in the consumption of the same prey species by predator 2. This can indicate a possible competition for the resource between predator 1 and 2. However, a negative correlation between the does not imply that there is a competition for resources. Similarly, a positive correlation does not necessarily imply a bottom-up trophic control.

3.6 Model evaluation

The model evaluation was performed by using the initial outputs and the observed ecological patterns to constrain the model to compare and check for irregularities. The time-series of

biomass and fluxes are compared as well as the diet patterns. Lastly, these patterns are compared to the knowledge of experts in their respective fields to check for further irregularities.

The model sampling was also evaluated for its performance. This was done by inspecting the Markov chain Monte Carlo (MCMC) sampling chains to check for autocorrelation. A lack of autocorrelation indicates proper sampling of the model.

A sensitivity analyses was not performed on the model. This omitted because of a lack of time. Ordinarily, this would be the protocol for conducting model evaluations. As CaN models are different to other models such as Ecopath, a different sensitivity analyses approach needs to be employed. The analyses would include changing the implicit constraints and component parameters (Model input parameters) to their respective minimum and maximum value according to life history theory, metabolic theory of ecology (Savage et al., 2004a), allometric relationships (Gillooly et al., 2001; Makarieva et al., 2008; R. J. Williams et al., 2007; T. M. Williams et al., 2004; Yodzis & Innes, 1992), direct measurements (Johnstone et al., 1993), or adapted from models (Pedersen et al., 2021; Planque, Favreau, et al., 2022). Through these changes the sensitivity of the model can be seen by comparing the sampling outputs. The model evaluation report was written, following the OPE protocol (Planque, Aarflot, et al., 2022).

4 Results

The first unprocessed output from the model is a set of possible trajectories, each of which is composed of the initial conditions at the start of the model sampling, 12 species within the model domain and 87 fluxes for each year except the last. The total number of years in this model is 35 years. The time-series of biomass are derived from the raw model output.

4.1 Biomass trajectories

The output of the model is presented as the trajectories of the component's biomasses and their respective fluxes between one another. The biomass trajectories are presented with uncertainty that is given as input from the observational data (Figure 3). The model output for the pelagic and demersal fish species are constrained by observational/model time-series, such as stock and diet assessments. This makes their biomass trajectories narrower than those of the marine

mammals, as the quality of data is higher and is presented with more certainty. As a result, there are broader uncertainty bands for the marine mammals as compared to the pelagic and demersal fish species.
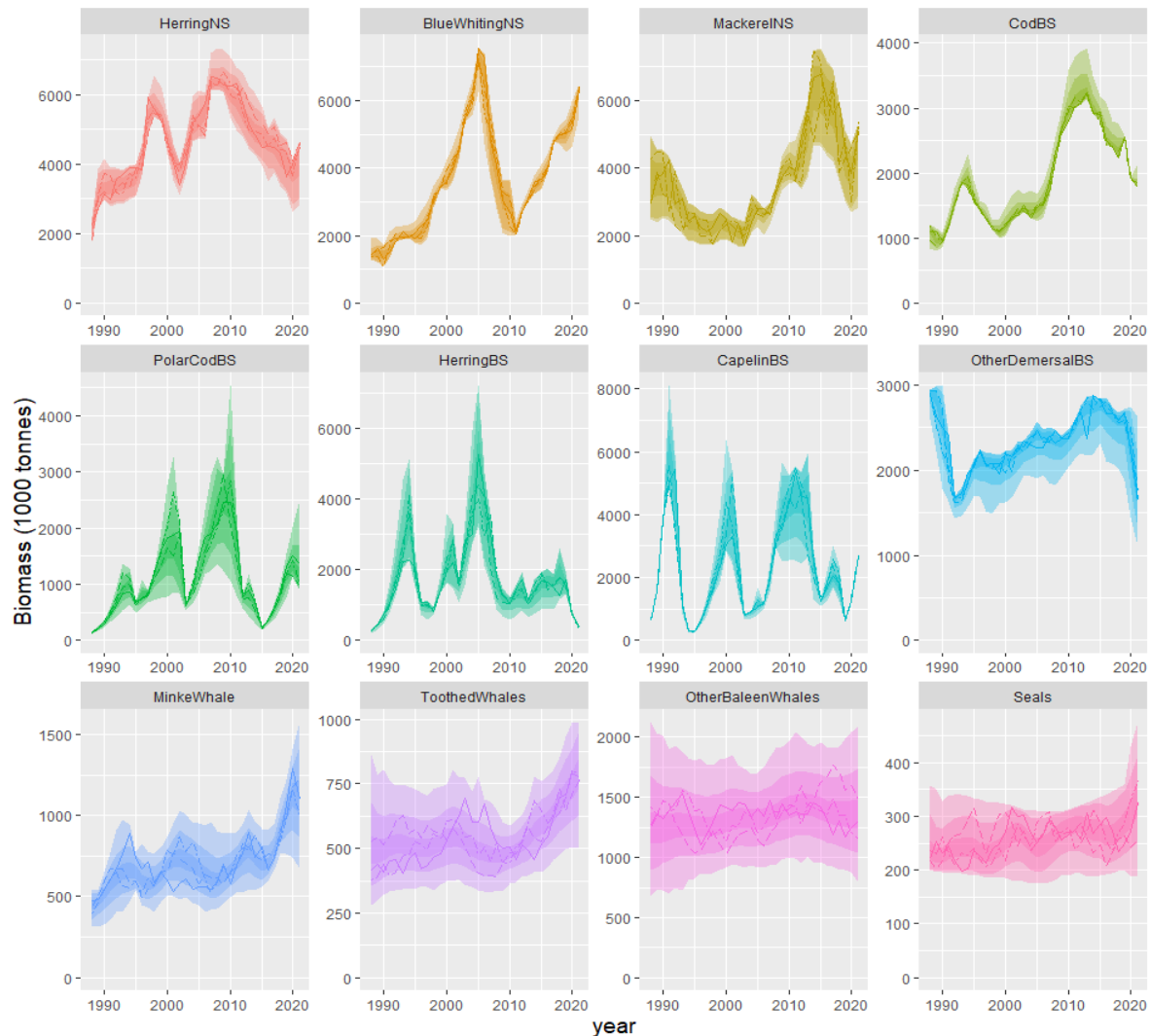
Figure 3. Reconstructed time-series of the biomasses for the 12 trophospecies within the model domain. Top row, left to right: adult herring, blue whiting, mackerel, cod. Middle row, left to right: polar cod, juvenile herring, capelin, other demersal fish. Bottom row, left to right: minke whale, toothed whales, other baleen whales, seals. Each plot shows the envelope of each component within the model domain. The colour luminance is correlated to the percentage of trajectories represented in it, 100% (light), 95% (medium), and 50% (dark). Three individual trajectories are randomly taken and are presented as a plain, dashed, and dash-dotted line (for illustration purpose).

4.2 Prey consumption by marine mammals

The prey consumption by marine mammals over time across all trajectories, shows the envelope of consumption by each marine mammal group for each prey across all years (Figure 4-7). The consumption by marine mammals is highly uncertainty due to the lack of annual diet data; the available data only provides mean values over time.

For minke whale as predator we can see that the consumption of capelin varies over time. These peak capelin consumptions overlap with the high biomass years for capelin. This shows that the biomass for capelin is high, minke whale can consume more. A similar pattern can be seen for the consumption of capelin by the other marine mammal groups.

For most other prey groups predated on by marine mammals, the uncertainty in consumption is high and shows little interannual variation. Where the overall trend of the consumption mimics the biomass trajectory of the respective marine mammal groups.
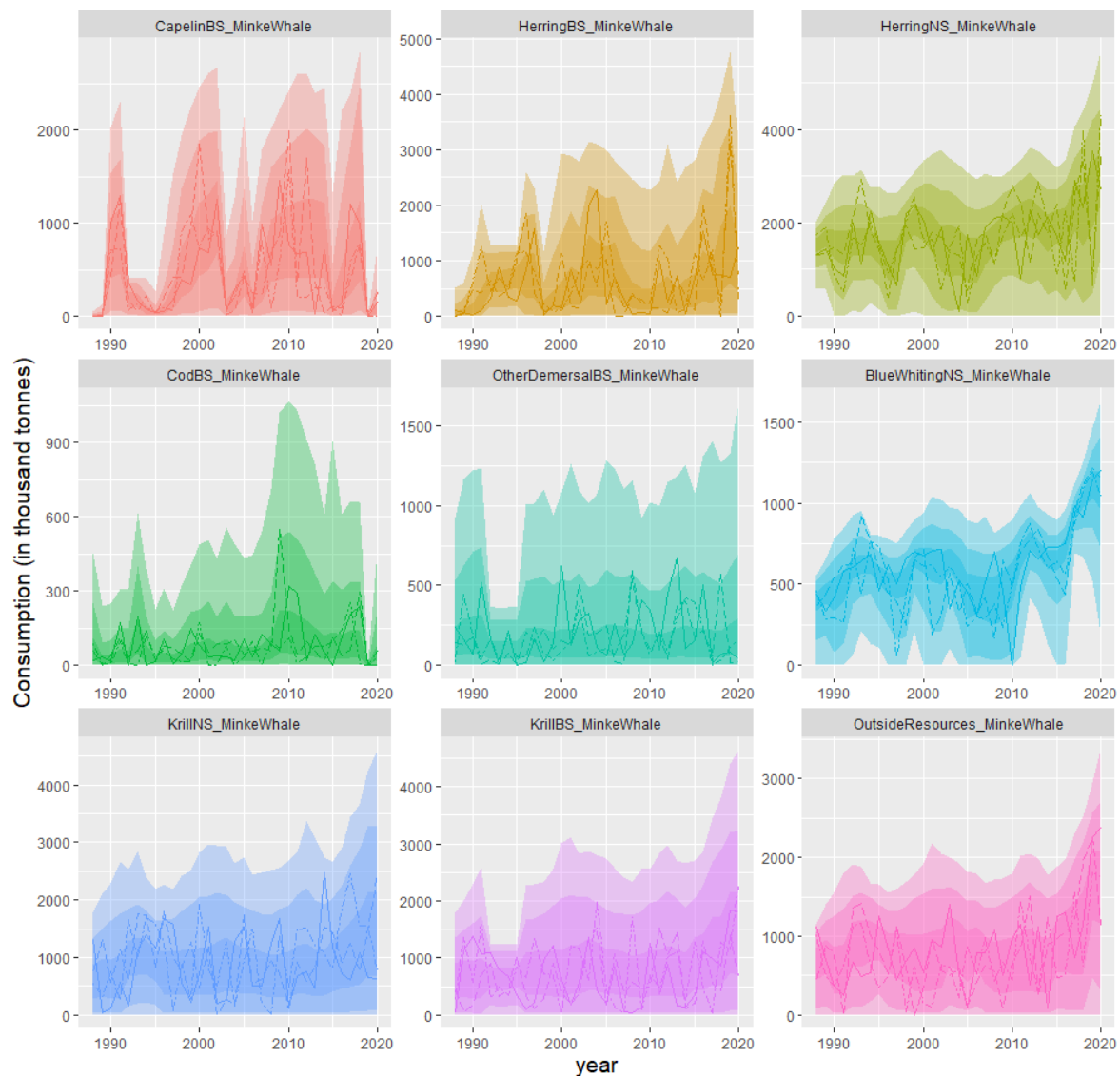
Figure 4. Reconstructed time-series of the consumption by minke whale of different prey species. Top row, left to right: capelin, herring in the Barents Sea, herring in the Norwegian Sea. Middle row, left to right: cod, other demersal fish, blue whiting. Bottom row, left to right: krill in the Norwegian Sea, krill in the Barents Sea, resources outside the Norwegian and Barents Seas. The envelope is similar to those previously described in Figure 3, with each plot showing the envelope of each flux from component to component. The colour luminance is correlated to the percentage of trajectories represented in it, 100% (light), 95% (medium), and 50% (dark).

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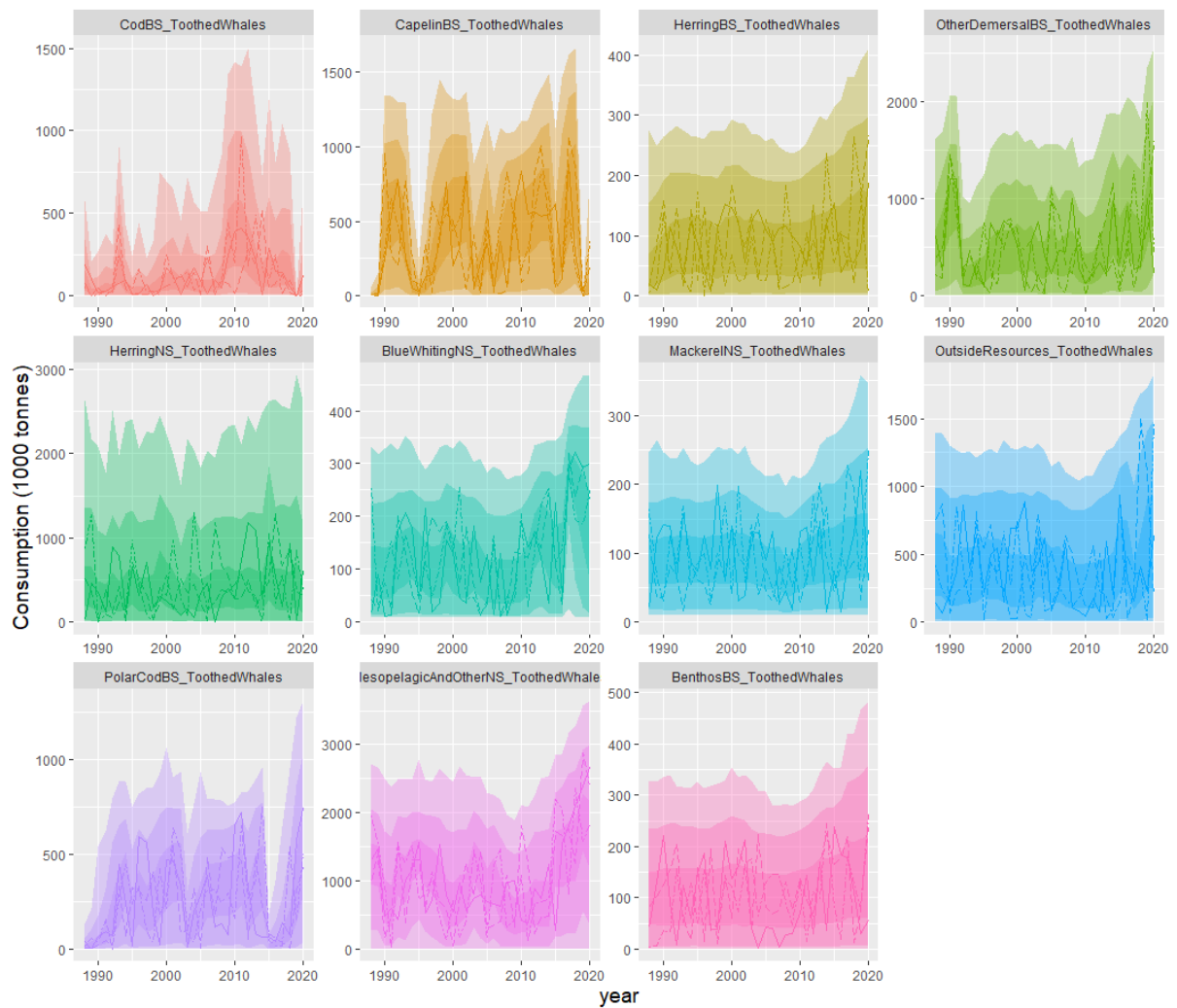
Figure 5. Reconstructed time-series of the consumption by toothed whales of different prey species. Top row, left to right: cod, capelin, herring in the Barents Sea, other demersal fish. Middle row, left to right: herring in the Norwegian Sea, blue whiting, mackerel, resources outside the Norwegian and Barents Seas. Bottom row, left to right: polar cod, mesopelagic organisms and other fish in the Norwegian Sea, and benthic organisms. The envelope is similar to those previously described in Figure 3, with each plot showing the envelope of each flux from component to component. The colour luminance is correlated to the percentage of trajectories represented in it, 100% (light), 95% (medium), and 50% (dark).
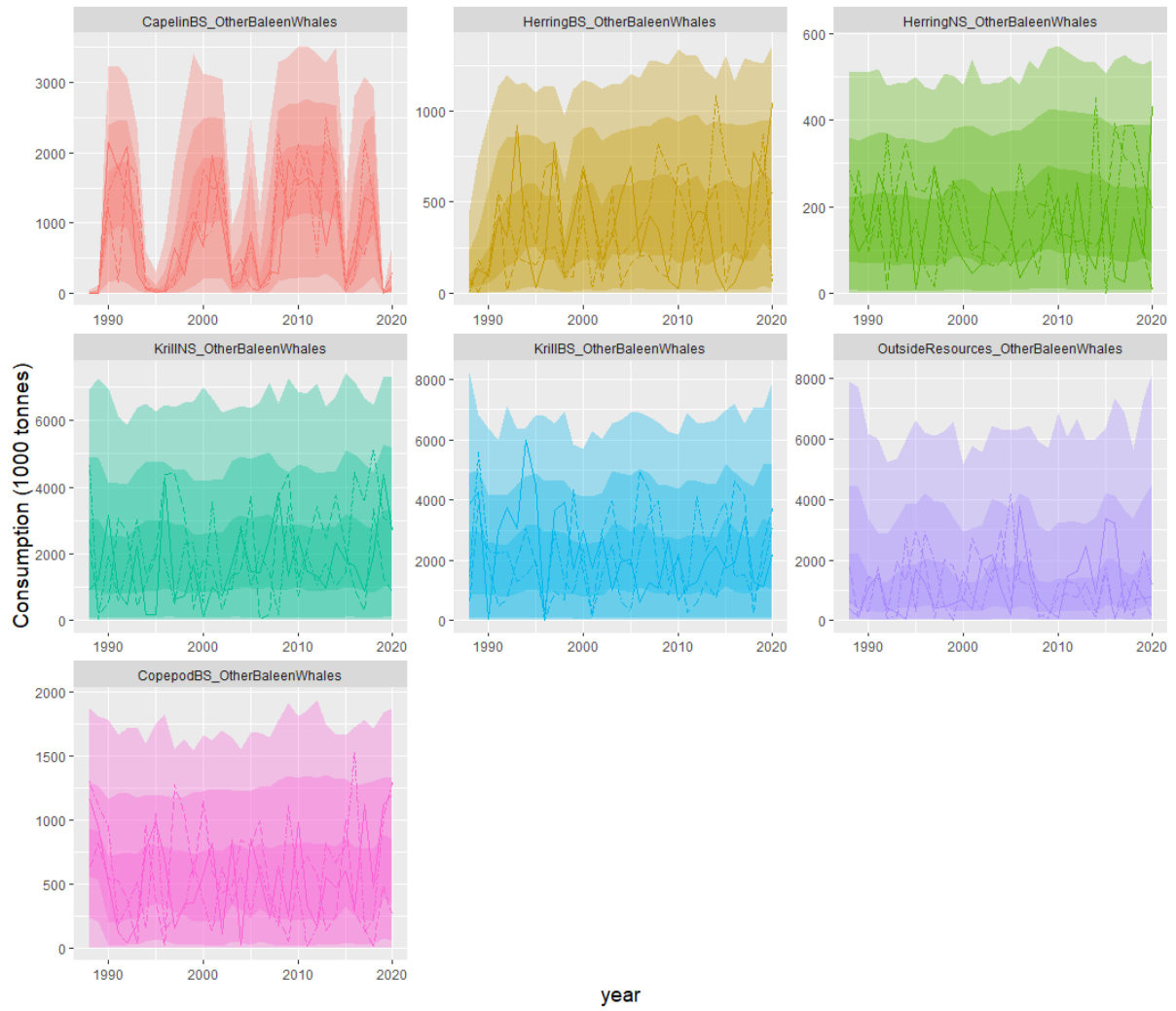
Figure 6. Reconstructed time-series of the consumption by other baleen whales of different prey species. Top row, left to right: capelin, herring in the Barents Sea, herring in the Norwegian Sea. Middle row, left to right: krill in the Norwegian Sea, krill in the Barents Sea, resources outside the Norwegian and Barents Seas. Bottom row: copepods. The envelope is similar to those previously described in Figure 3, with each plot showing the envelope of each flux from component to component. The colour luminance is correlated to the percentage of trajectories represented in it, 100% (light), 95% (medium), and 50% (dark).

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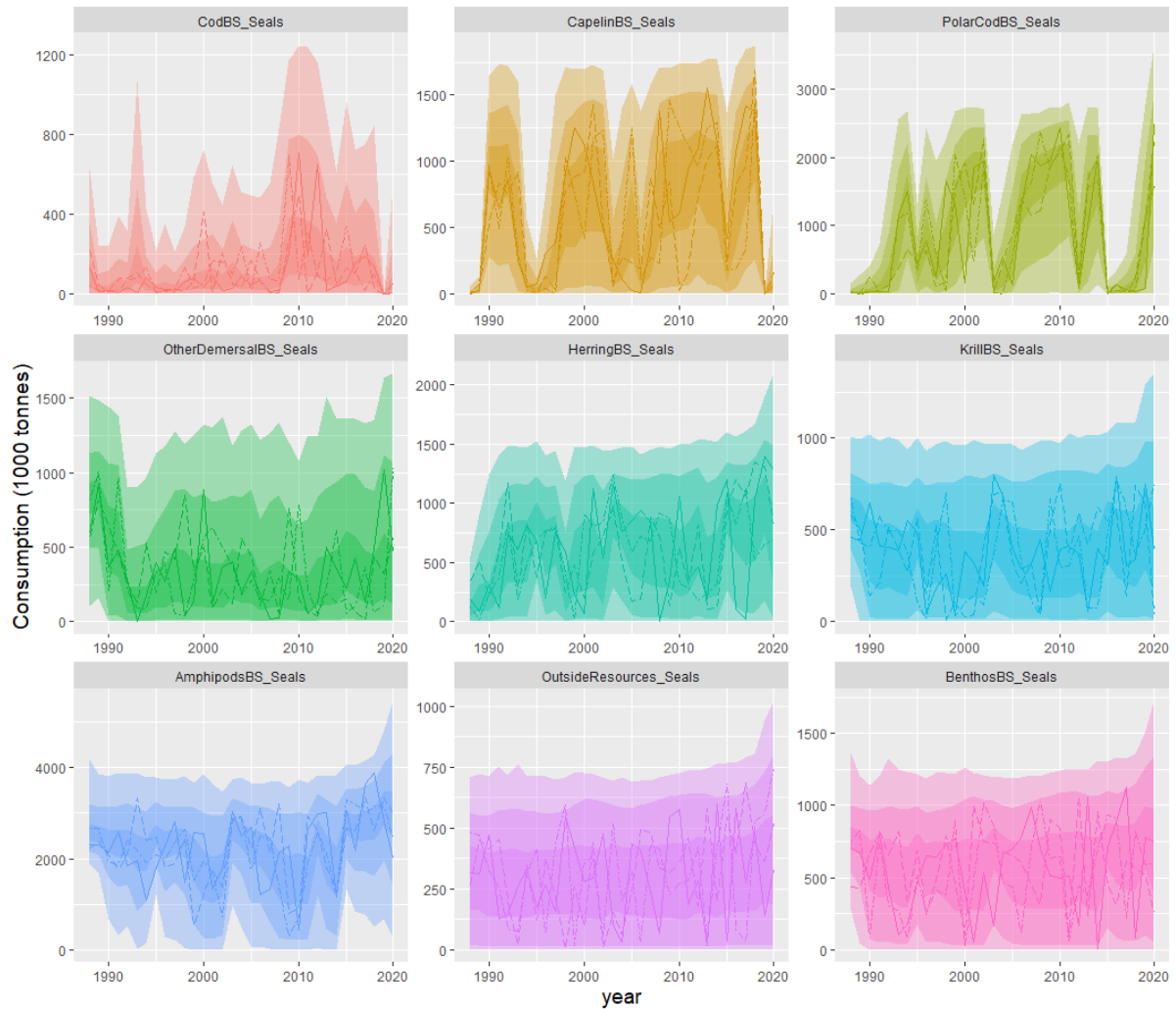
Figure 7. Reconstructed time-series of the consumption by other baleen whales of different prey species. Top row, left to right: cod, capelin, polar cod. Middle row, left to right: other demersal fish, herring in the Norwegian Sea, herring in the Barents Sea. Bottom row: amphipods, resources outside the Norwegian and Barents Seas, benthic organisms. The envelope is similar to those previously described in Figure 3, with each plot showing the envelope of each flux from component to component. The colour luminance is correlated to the percentage of trajectories represented in it, 100% (light), 95% (medium), and 50% (dark).

4.3 Diets

The consumption trajectories can be used to derive diet estimates for the trophospecies in the model domain (Figure 8). The consumption across years and CaN trajectories can be summarised by averaging the sum of the flows across each trajectory. The difference in consumption between trophospecies is clearly visible within Figure 8, with the highest consumption accounted for by blue whiting and lowest by birds. These consumption outputs are constrained by the life history parameters and the biomass of the predator trophospecies. However, where estimations on total annual consumption are available, they are used to constrain the model. This is the case for, for example, cod, minke whale, toothed whales, other

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baleen whales and seals. In Figure 8, the difference in total annual consumption/catch can be seen by comparing the consumption by marine mammals to that of the catch made by the fisheries. On average, the marine mammals consume about 19,952 thousand tonnes annually (95%CI: [19,524; 20,355]) and fisheries catch on average 3,832 thousand tonnes annually. This leads to a 5.2 (95%CI: [5.09; 5.31]) times higher consumption from the marine mammals compared to the fisheries removal.
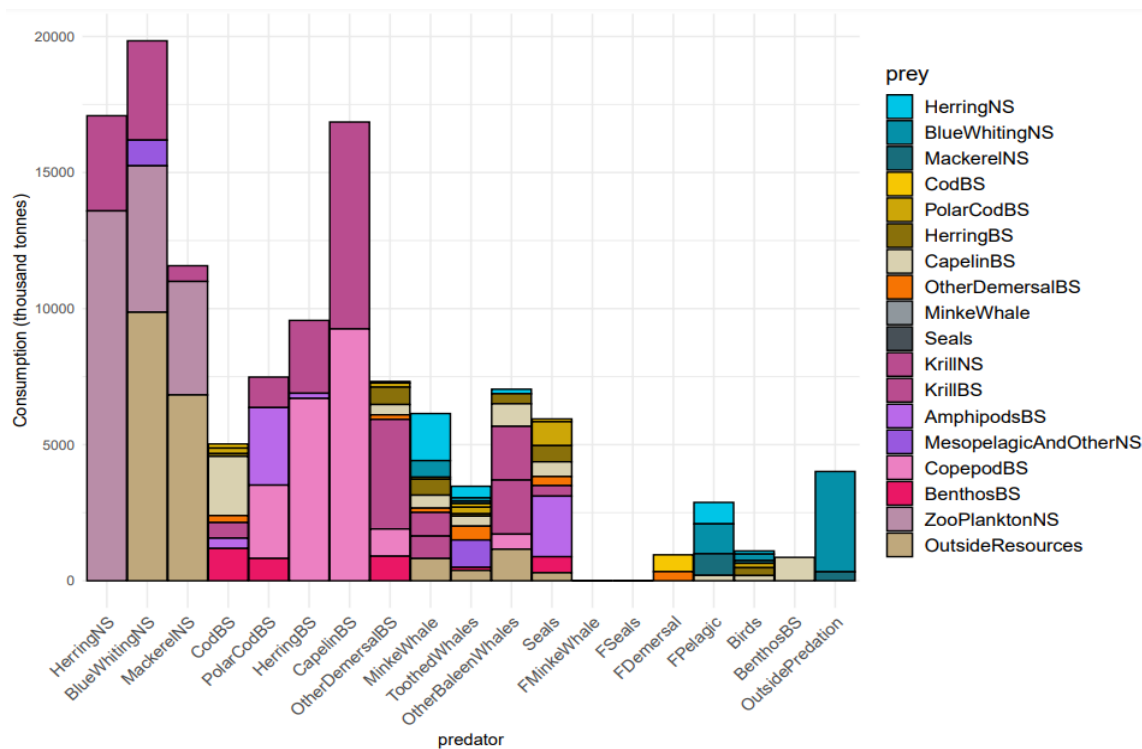
Figure 8. Mean annual prey consumption per trophospecies over the entire model duration (1988-2021) and across all CaN trajectories. On the y-axis, the consumption in thousand tonnes is projected, with all the trophospecies on the x-axis. The colour of the bar corresponds to the total consumption by that trophospecies of a specific prey (listed in the legend).

Alternativly, consumption per unit biomass (CoB) can be derived by deviding the consumption of a species by its biomass (Table 3). Looking at the CoB, it is clearthat the highest average CoB is by seals (22.7, 95% CI: [22.5:22.8]), and the lowest is by cod (2.9, 95% CI: [2.8:2.9]).

A similar method can be used to define the outflow from a trophospecies. The outflow is the total amount of flow out of the compartment by predation or hunting, which can be standardised by dividing it by respective biomass of the trophospecies (PFoB; Table 3). This is the predation/fisheries catch over biomass (PFoB). The output of the model demonstrates that the highest average PFoB is displayed by capelin (2.6, 95% CI: [2.4:2.8]) followed by blue whiting

(1.6, 95% CI: [1.5;1.7]). These species display the highest loss of biomass and are subject to the most predation or other form of loss. In the case of capelin, it is due to a high predation pressure combined with life history. As capelin represent a large percentage of the total consumption by predators such as cod, other baleen whales, and seals. Capelin is also known to suffer high mortality after spawning. The lowest PFoB is tied between the toothed and other baleen whales (NA) as these components do not have any predation or hunting in the model.

Table 3. Model outputs for each trophospecies within the model domain. This includes average biomass, inflow into the trophospecies, consumption over biomass (CoB), outflow out of the trophospecies, and predation/fisheries over biomass (PFoB). Each value is given with the 95% confidence interval.

Species	Biomass	Inflows	CoB	Outflows	PFoB
HerringNS	4,577 [4,436;4,730]	17,087 [16,589;17,607]	3.7 [3.7; 3.8]	3,222 [3,046;3,396]	0.7 [0.7;0.7]
BlueWhitingNS	3,606 [3,518;3,691]	19,840 [19,435;20,23]	5.5 [5.4;5.6]	5,760 [5,590;5,934]	1.6 [1.5;1.7]
MackerelNS	3,567 [3,405;3,720]	11,575 [11,113;12,013]	3.2 [3.2; 3.3]	1,317 [1,246;1,388]	0.4 [0.3;0.4]
CodBS	1,899 [1,874;1,928]	5,025 [4,937;5,113]	2.6 [2.6; 2.7]	1,129 [1,084;1,175]	0.6 [0.6;0.6]
PolarCodBS	1,081 [978;1,179]	7,484 [6,985;7,957]	6.9 [6.7; 7.2]	1,639 [1,562;1,718]	1.5 [1.4;1.7]
HerringBS	1,748 [1,608;1,893]	9,566 [9,024;10,128]	5.5 [5.3; 5.7]	2,660 [2,455;2,869]	1.5 [1.4;1.7]
CapelinBS	2,342 [2,197;2,485]	16,856 [16,109;17,576]	7.2 [6.9; 7.5]	6,019 [5,716;6,323]	2.6 [2.4;2.8]
OtherDemersalBS	2,331 [2,283;2,375]	7,324 [7,172;7,457]	3.1 [3.1; 3.2]	1,764 [1,701;1,826]	0.8 [0.7;0.8]
MinkeWhale	698 [685;710]	6,145 [6,022;6,246]	8.8 [8.8; 8.8]	3 [3;3]	0.0 [0.0;0.0]
ToothedWhales	544 [534;555]	3,472 [3,417;3,525]	6.4 [6.3;6.4]	NA [NA;NA]	NA [NA;NA]
OtherBaleenWhales	1,331 [1,304;1,357]	7,038 [6,911;7,160]	5.3 [5.2;5.3]	NA [NA;NA]	NA [NA;NA]
Seals	260 [253;265]	5,945 [5,788;6,056]	22.9 [22.7;23.1]	4 [4;4]	0.0 [0.0;0.0]

The diet of trophospecies is calculated by dividing the flow by the sum of flows for the consumption by predators. The resulting diet is reflective of the data provided in the constraints. It is noteworthy that the majority of available data pertains to the mean proportion in diet set over a number of years, as determining the total consumption of prey by predator is a more challenging measure to obtain and is not common.

The diet of minke whale appears to be varied, with the biggest contributor being Norwegian spring spawning herring and krill. Toothed whales have the biggest diet variety among the marine mammal groups, with the mesopelagic organisms and other fish composing the highest proportion in their diet. Other baleen whales predominantly feed on krill, however, also display a large prey diversity. The seals have the amphipods as the highest proportion in the diet.

The benthos is displayed as a predator consuming capelin (Figure 9). This non-trophic link represents the spawning mortality of capelin. As capelin is known to suffer high mortality after spawning. This annual flux is on average 860 thousand tonnes.
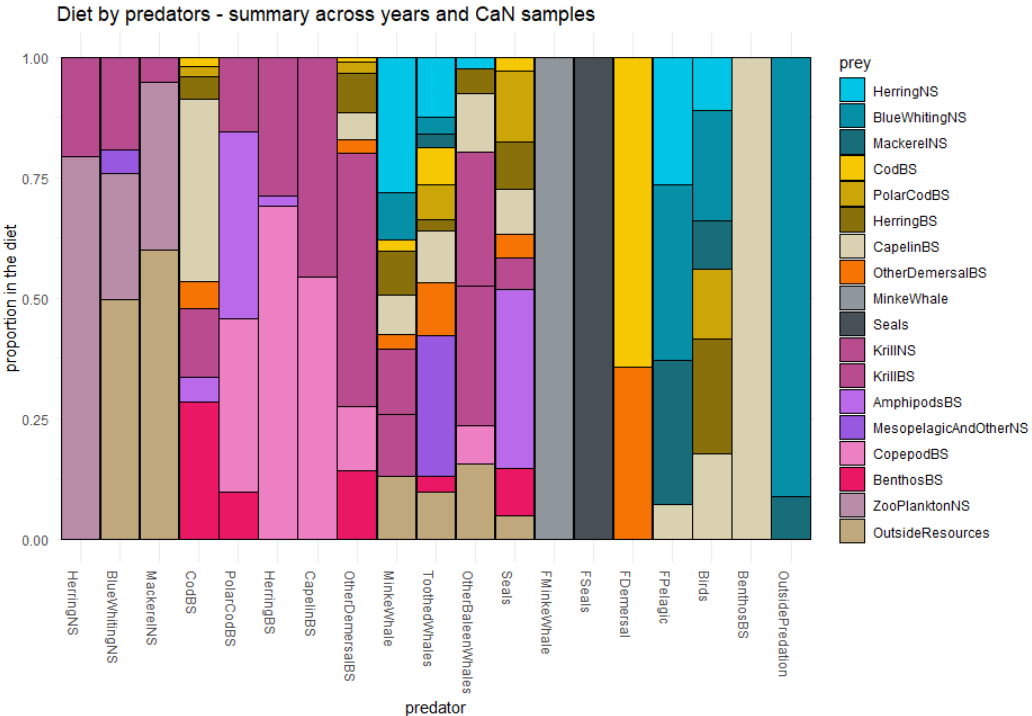
Figure 9. Diets of the predator trophospecies. The y-axis displays 0 to 1 showing the proportion of each prey in the diet of the predator. The colours are corresponding to the prey, shown in the legend.

4.4 Direct and food-web mediated interactions

4.4.1 Direct interactions

4.4.1.1 Norwegian Sea

In the Norwegian Sea direct interactions are considered between the consumption by marine mammals and the fisheries for the three commercial pelagic fish stocks, Norwegian spring spawning herring, blue whiting, and Atlantic mackerel (Figure 10). When looking at all the direct correlations in the Norwegian Sea, there is an overarching slight positive correlation coefficient for most correlations presented. For the direct interaction relationship regarding Norwegian spring spawning herring as prey, there are two relationships: that of the adults only and that of the juveniles and adults together. The juveniles of the herring do not inhabit the Norwegian Sea, but the Barents Sea. However, the correlation between the fisheries and marine mammals for both herring groups is an interesting interaction to analyse, as the juvenile herring emigrate into the Norwegian Sea from the age of approximately 4 years old. Where they assimilate with the Norwegian spring spawning herring adults. Interestingly, the lowest correlation regards the Norwegian spring spawning herring as prey, with no correlation visible over the last 35. The correlation regarding blue whiting as the shared resource, presents the highest positive correlation. Indicating that the marine mammals and fisheries are not competing for blue whiting as a resource but rather feed opportunistically (Figure 10). Viewing the interaction from a broader perspective, by considering all commercial fish stocks in the Norwegian Sea, provides an additional means of analysis. This approach as stated shows a positive correlation. The positive correlation would indicate that in the Norwegian Sea there is evidence for limited competition for resources and predation by marine mammals and fish catch is rather opportunistic as prey becomes available. However, it is not possible to rule out the possibility of the correlation being negative.

The correlation coefficient between the consumption by marine mammals individually and the fisheries catch shows similar results (Figure 10, top-right, bottom-left and -right).

Figure 10. Distributions of the correlation coefficients between consumption by marine mammals and the fisheries catch for different prey species and groups in the Norwegian Sea. Each plot is different predator (group), with each boxplot within them representing the correlation between that predator and the fisheries in relationship to the prey. The prey is represented by different colours and are abbreviated following the List of abbreviations. A positive correlation indicates that an increase in the consumption of one prey species by marine mammals corresponds to a concurrent increase in the catch of the same species by the fisheries. A negative correlation indicates that an increase in the consumption of one prey species by marine mammals corresponds to a concurrent decrease in the catch of the same species by the fisheries.

4.4.1.2   Barents Sea

In the Barents Sea, the direct interactions between the consumption by marine mammals and the fisheries catch for the commercially fished demersal and pelagic fish species are considered. Upon examining the correlation coefficients presented in Figure 11, a common trend of positive correlations is observed across various species and groups, including cod, capelin, and all fish species modelled in the Barents Sea. These correlations indicate that competition between marine mammals and fisheries for these fish as resources is not present within the model. Instead, it seems that marine mammals and the fisheries rather consume or catch opportunistically when these fish become available. When the marine mammals are evaluated independently, a similar trend is present in terms of their positive correlation with specific prey

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species, albeit with a lower correlation coefficient. These weaker coefficients suggest less compelling evidence for interactions between the marine mammals and fisheries for prey.

The contrary is true for the other demersal fish as a resource. The analysis reveals a distinct negative correlation between the consumption of demersal fish by marine mammals and the corresponding catch from fisheries. This suggests that the marine mammals and fisheries may compete for this resource. Other baleen whales, toothed whales, and seals, all show a similar correlation pattern for other demersal fish as prey. However, this pattern is not present for minke whale. This correlation is close to zero and shows no sign of a potential resource competition with the fisheries.
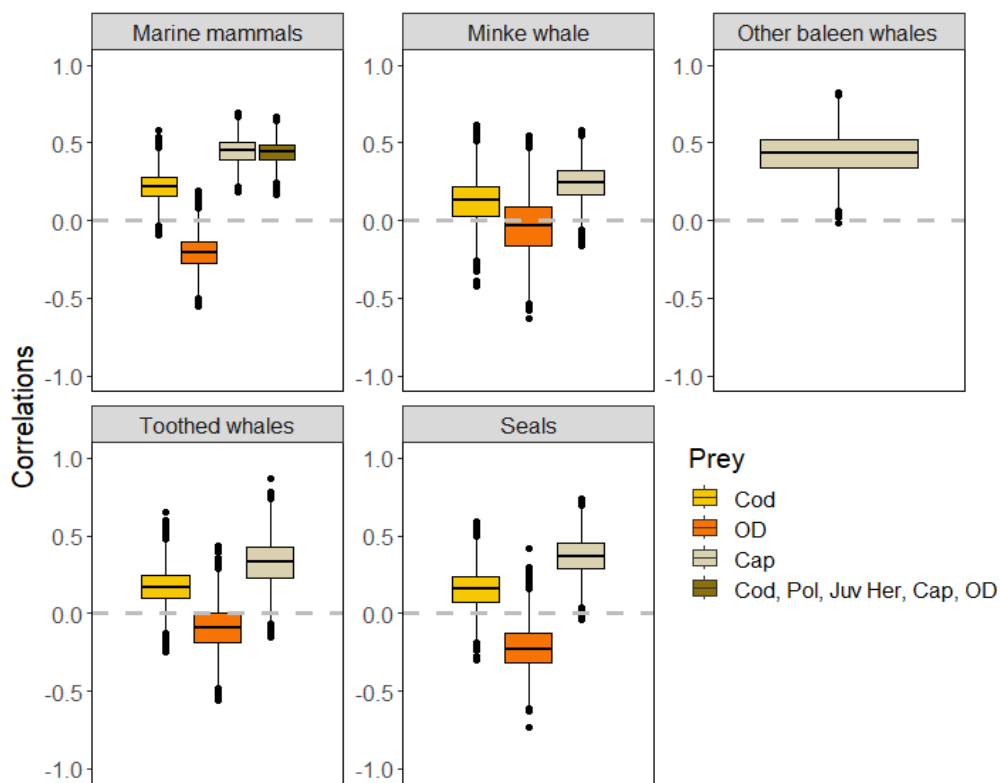
Figure 11, Distributions of the correlation coefficients between consumption by marine mammals and the fisheries catch for different prey species and groups in the Barents Sea. Each plot is different predator (group), with each boxplot in them representing the correlation between that predator and the fisheries in relationship to the prey. The prey is represented as the different colours and are abbreviated following the List of abbreviations. A positive correlation indicates an increase in the consumption of one prey species by marine mammals corresponds to a concurrent increase in the catch of the same species by the fisheries. A negative correlation indicates with an increase in the consumption of one prey species by marine mammals corresponds to a concurrent decrease in the catch of the same species by the fisheries.

4.4.2   Food-web mediated interaction

Food-web mediated interactions are represented as potential competition between predators that can have implications on the interaction between marine mammals and fisheries.

Krill in the Barents Sea as prey shows four correlations in Figure 12 (top-middle). When cod, other demersal fish, and all Barents Sea fish are considered as krill's predator there is slight positive correlation between them and marine mammals. However, the correlation between krill consumed by capelin and marine mammals is negative. Thus, there is potential competition between capelin and marine mammals for krill.

When the Norwegian Sea and Barents Sea are combined, there is a negative correlation between the consumption of krill by marine mammals and by all fish species described in the model. The interaction suggests a possible, but limited, competition.

Notably, when capelin is analysed as a prey species instead of a predator, there is high positive correlation (Figure 12 middle-left). The findings suggest that there is no competition for capelin between marine mammals and demersal fish. Instead, both species seem to opportunistically feed on this resource when it is available. This is similar to the finding regarding juvenile herring as prey (Figure 12 middle-middle).

The Norwegian and Barents Seas can be compartmentalised into their own separate systems. Two correlations produced by the model give an overview of the interactions within these ecosystems. In the Norwegian Sea, the three pelagic fish stocks and marine mammals show no sign of competition, as the correlation indicates a positive correlation (Figure 12 middle-right). This can indicate a more opportunistic feeding interaction for their shared prey of krill, zooplankton, and mesopelagic and other fish species when they are available. In the Barents Sea the five trophospecies and marine mammals could be competing for resources. They show a negative correlation between the consumption by marine mammals and Barents Sea fish species for the resources outside of the model domain, containing, krill, copepods, amphipods and benthic organisms (Figure 12 bottom-left).

When combining the Norwegian and Barents Seas, the interaction between the marine mammals and all fish species in total shows a correlation that is negative (Figure 12 bottom-

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middle). This indicates that, between marine mammals and all fish species considered inside the model domain, there is a possible competition for resources.
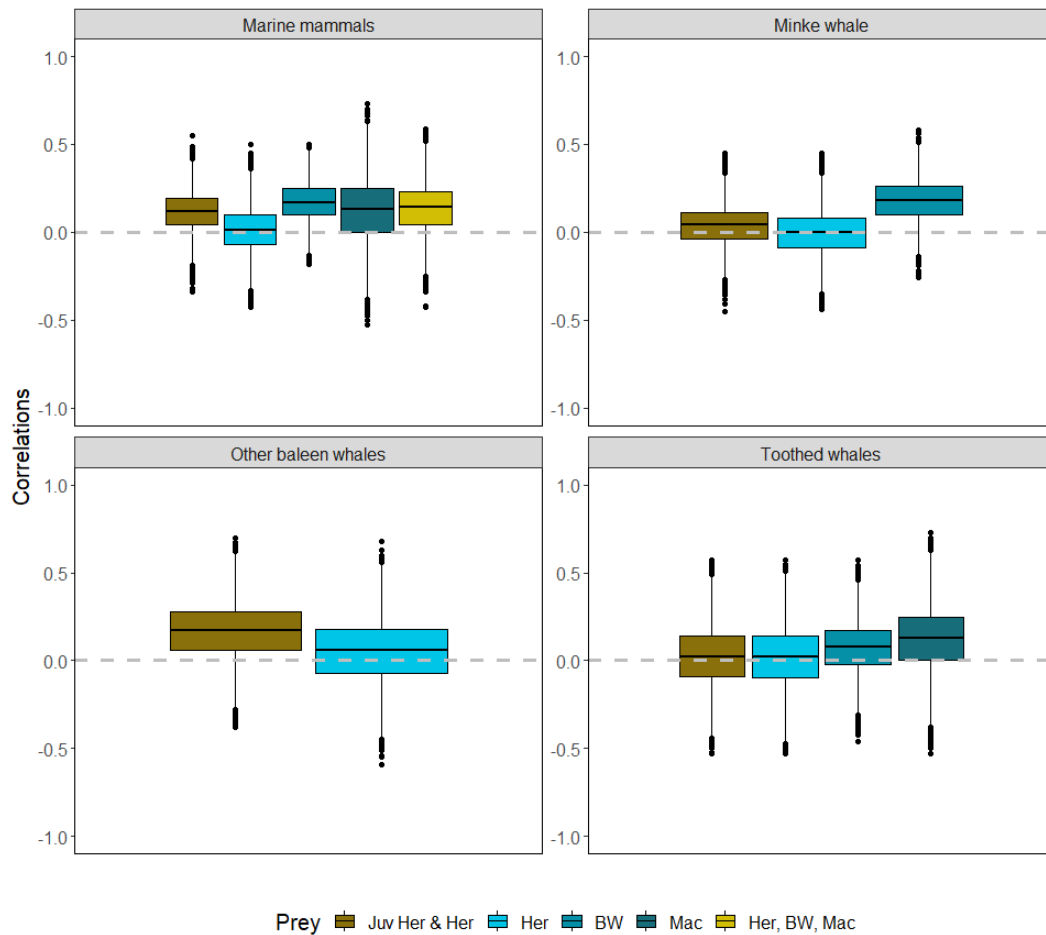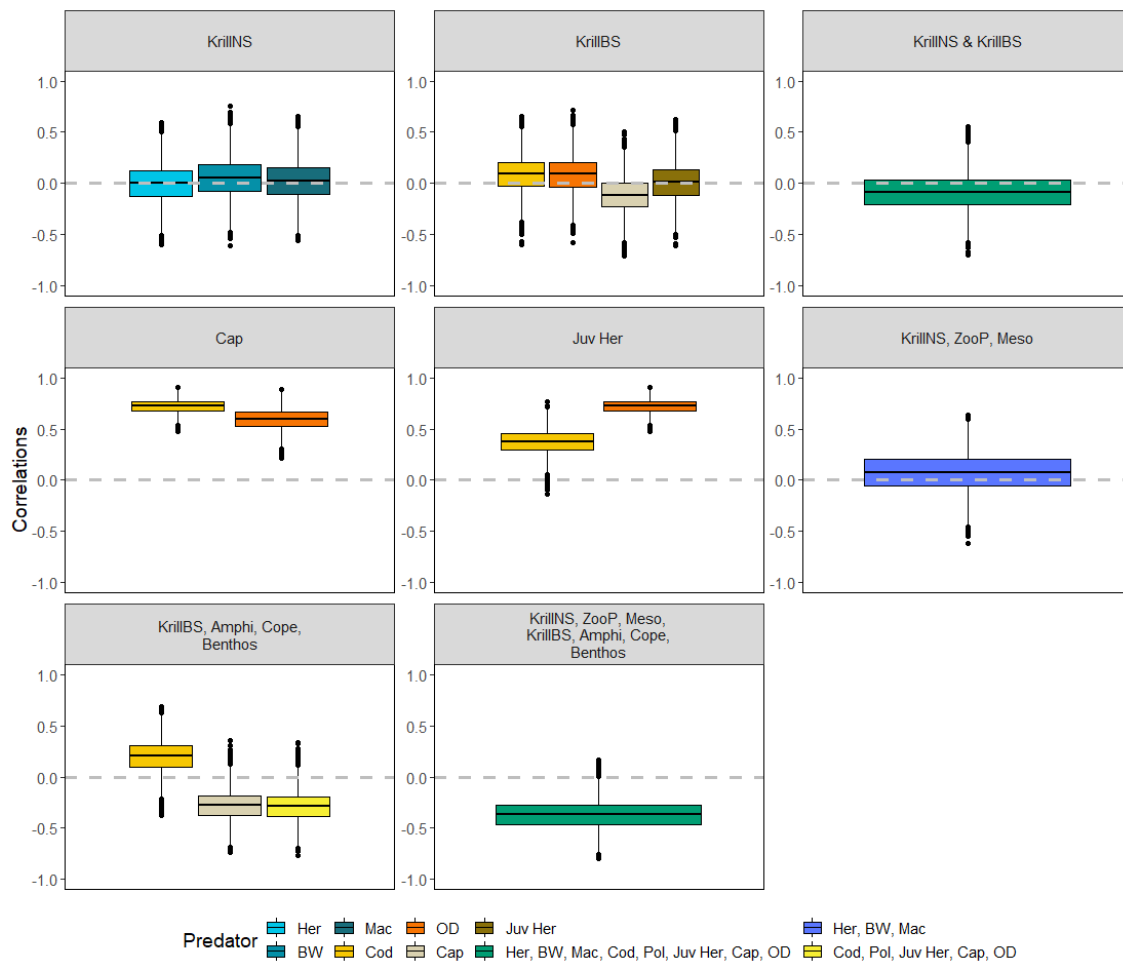

Figure 12. Distributions of the correlation coefficients between consumption by marine mammals and by other predator groups for different prey species. Each plot is a different prey (group) abbreviated following the List of abbreviations, with each boxplot in them representing different predators. They are represented by different colours and are abbreviated following the List of abbreviations. A positive correlation indicates that an increase in the consumption of one prey species by marine mammals corresponds to a concurrent increase in consumption of the same species by the other predator. A negative correlation indicates that an increase in the consumption of the prey species by marine mammals corresponds to a concurrent decrease in consumption of the same species by the other predator, or vice-versa.

4.4.2.1 Minke whale

The distribution of correlation coefficients concerning minke whale against different predator(s)(groups) can be seen in Figure 13. The overall distribution of the plots is fairly similar to the plots that include other marine mammals (Figure 12). However, the correlations for minke whale appear to be weaker. Nonetheless, the interactions regarding capelin and juvenile herring as prey display a positive correlation (Figure 13 bottom-middle and -left).

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Capelin, when considered as a predator, exhibits the same correlation coefficient distributions as those produced when all marine mammals were grouped with krill as the prey (Figure 12 top-middle). The interactions display a possible resource competition. When the total consumption of capelin is considered, with all the prey species, the correlation remains slightly negative indicating a possible competition (bottom-left).
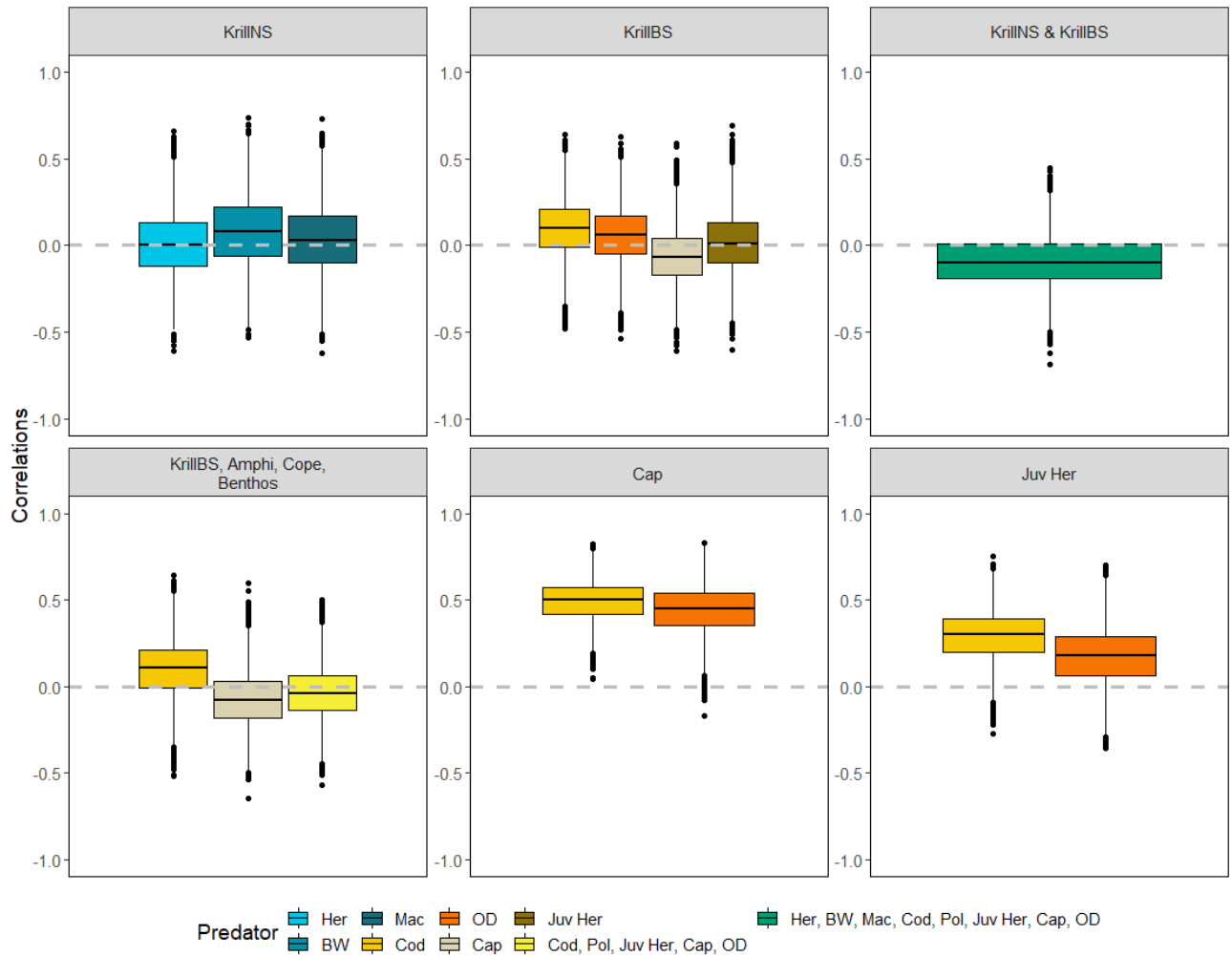
Figure 13. Distributions of the correlation coefficients between consumption by minke whales and by other predator groups for different prey species. Each plot is a different prey (group) abbreviated following the List of abbreviations, with each boxplot in them representing different predators. They are represented by different colours and are abbreviated following the List of abbreviations. A positive correlation indicates that an increase in the consumption of one prey species by marine mammals corresponds to a concurrent increase in consumption of the same species by the other predator. A negative correlation indicates that an increase in the consumption of the prey species by marine mammals corresponds to a concurrent decrease in consumption of the same species by the other predator, or vice-versa.

4.4.2.2 Other marine mammal groups

The other marine mammals – i.e., toothed whales, other baleen whales and seals – are also considered individually for their consumption correlation patterns. They are presented in Food-

web mediated interaction, and show patterns that are similar to the previously presented correlation patterns for minke whale (Figure 13). The most interesting result is the negative correlation that is present between the consumption by seals and by capelin, when all prey is jointly considered. This is similar to the pattern that emerges when all marine mammals are combined, but this correlation pattern is not present, however, for the other three marine mammal groups when considered individually.

5 Discussion

With the use of CaN modelling, we reconstructed a collection of possible trajectories of the Norwegian and Barents Sea food-web spanning the last three decades, in compliance with existing data and knowledge. The uncertainty in the trajectories points to the uncertainty of the available data and time-series. Missing information about the ecosystem could have affected the output. However, one of the strengths of this modelling approach is that, despite having missing data, the model still performs within the constraints that are set on other components in the ecosystem. The collection of trajectories was used to structure the average diet composition of each component in the model. The model produced a diet composition for all included trophospecies that resembled their known diet. The correlation patterns show how consumption/catch by one group has varied in relation to the consumption/catch by another.

The findings of this study suggest that, in the modelled ecosystem of the Norwegian Sea, there is evidence of direct and food-web mediated interactions that exhibit a weak bottom-up control, a weak top-down control, or a combination of both trophic controls. In the Barents Sea, marine mammals' consumption and fisheries catch of capelin and cod appear to be synchronised in terms of removal. This is representative of a rather opportunistic feeding- and catch-regime. In contrast, the model shows evidence for a potential competitive interaction between the marine mammals and the fisheries for other demersal fish species as prey. The correlation for this competition, however, is not very strong.

For the food-web mediated interactions, the pattern with capelin as prey continues. The interaction between marine mammals and demersal fish as predators is bottom-up driven by capelin. Not surprisingly, when capelin is used as a predator, the interactions between marine mammals and capelin for planktonic prey shows mostly competitive interactions. Indicating that resource competition was present over the last 35 years (Figure 12, top-middle). This can

indicate that the strongly-fluctuating capelin biomass may be driving this interaction. To investigate the influence of the dynamics of capelin on the ecosystem, a more in-depth evaluation of capelin is warranted.

The interaction between marine mammals and demersal fish shows a weak positive correlation in relation to krill as their shared resource. This weak positive correlation represents a slight bottom-up control by krill, but the possibility of no correlation cannot be excluded.

An important aspect of the design of the model is that it provides a comprehensive depiction of the possible trajectories of the Norwegian and Barents Sea ecosystems over the last 35 years (1988-2021). Hence, the results obtained from the model are exclusively applicable to past ecological patterns, and no definitive inferences regarding future ecosystem dynamics can be made based on this current model.

5.1 Consumption estimates

We compared the consumption over biomass (CoB) numbers acquired from the model output to those in previous literature. We can see that, for minke whale, our CoB of 8.8 falls in the middle of most other reported values in scientific literature. Blanchard et al. (2002), who calculated the Q/B by using the yearly ration and body weight, derived a value of 9.9. Dommasnes et al. (2001) obtained a value of 8.14. Our model output is consistent with these values. It should be noted that a CoB extrapolated from certain values[1] for average biomass and consumption for minke whale in Skern-Mauritzen et al. (2022) was calculated to be 5.5. As our CoB is based on the model input parameters and the limitations set on the biomass and consumption of each species, our relatively higher CoB can either be attributed to a higher consumption, a lower biomass, or a combination of both.

For toothed whales and other baleen whales in the model, the CoB outputs are also consistent with the values reported in previous literature. The reported CoB values for toothed whales are 4.9, 6.2, and 12.75 from Dommasnes et al. (2001), Skern-Mauritzen et al. (2022), and Blanchard et al. (2002), respectively. We obtained a CoB value of 6.4. The value of 12.75, reported by

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[1] The values used were taken from data on marine mammals in the Greenland and Barents Seas in Skern-Mauritzen et al. (2022). The geographical extent of the Greenland Sea used in their paper includes the Norwegian Sea. This discrepancy has been accounted for in our model's constraints.

Blanchard et al. (2002), was calculated exclusively for the Barents Sea and was based on the consumption rates of only a few species – white-beaked dolphins, harbour porpoise, and orca – which are a small subset of the species considered in our model. Similarly, Dommasnes et al. (2001) includes only white-beaked dolphins, harbour porpoise, orca and sperm whale, meaning that their value also provides an incomplete representation of the ecosystem. Skern-Mauritzen et al. (2022) included a similar species composition to our model.

The reported CoB values for other baleen whales are 6.56, 3.0, and 13.11 from Dommasnes et al. (2001), Skern-Mauritzen et al. (2022), and Blanchard et al. (2002), respectively. Our value of 5.3 falls within the range of these values. As stated in the paragraph above, the CoBs reported by Dommasnes et al. (2001) and Blanchard et al. (2002) for other baleen whales are not based on the same set of species used in our model.

Seals show a higher CoB (22.9) in our model as compared to other studies, such as Dommasnes et al. (2001) (14.52), Skern-Mauritzen et al. (2022) (12.7), and Blanchard et al. (2002) (15.59). One potential explanation for this discrepancy may be a high value for other losses in the Model input parameters. Consequently, the total consumption by seals in our model may be an overestimation in comparison to real-life scenarios. To assess the accuracy of the model's CoB value and of the value for other losses in the model, further discussion with experts is warranted.

The average annual consumption by marine mammals in the model is constrained by information from Skern-Mauritzen et al. (2022). The behaviour of the model can be analysed by comparing the model results to the input data. In doing so, it is evident that the average annual consumption by the marine mammal groups in the model are close to the upper limit of annual consumption reported by Skern-Mauritzen et al. (2022) (Table 3, Inflows). This could be explained by a few things. The mean annual consumption by marine mammals provided by Skern-Mauritzen et al. (2022) may be on the lower side, with the 95% confidence interval only marginally covering the mean annual consumption necessary in the model. Alternatively, it could be due to an artefact of the model: the constraints provided a large amount of freedom around the consumption by marine mammals thus allowing for much of the loss of biomass of fish trophospecies to be attributed to marine mammal consumption. Minke whale has been identified as an important species within the Norwegian and Barents Sea ecosystem, especially in regard to their total consumption and ability to contribute to major mortality rates of capelin

and juvenile herring (Haug et al., 2002; Lindstrøm et al., 2002; Smout & Lindstrøm, 2007; Tjelmeland & Lindstrøm, 2005). Haug et al. (2002) showed that, from 1992 to 1994, the relative importance of capelin as prey for minke whale decreased from around 0.8 to 0. This change was explained by the decline in capelin abundance in that period. When the flux in our model from capelin to minke whale and the capelin biomass trajectories are compared, a similar pattern to the one described by Haug et al. (2002) is observed. This shows that when capelin is available, it is an important part of the diet of minke whales.

5.2 Trophic interactions within the food-web

The importance of capelin in the Barents Sea ecosystem has been emphasized in previous studies (Bogstad et al., 2015; Gjøsæter, 1998; Hop & Gjøsæter, 2013). This study confirmes the role of capelin in the ecosystem. When capelin was investigated as a prey species, our model showed that the direct interaction between the marine mammals and fisheries is bottom-up driven. This means that the biomass of capelin drives the consumption of the predators.

The model supports past competition between capelin and marine mammals. This is present throughout the individual marine mammal groups (Figure 10), where krill was competed for. This could imply the existence of a marine mammal-fisheries interaction that is food-web mediated.

However, as mentioned before, the biomass of capelin is the main driver for the consumption bymany predators in the Barents Sea marine ecosystem. Together with the high fluctuations of biomass of capelin, this might indicate that the negative correlation derived from the model outputs is not caused by a competition for resources but by the capelin collapses that have occurred during the last 35 years (Hop & Gjøsæter, 2013; Jakobsen & Ozhigin, 2011; Yndestad & Stene, 2002). Other papers have suggested that the collapse of capelin was caused by overexploitation by fisheries and predation by herring (Hjermann et al., 2004). The study results do not contradict this observation. However, the correlation analysis between marine mammals and fisheries demonstrates that there is no direct competition for capelin between the two groups present in our model. The capelin stockfluctuations are believed to be "functions of the ecological processes in the area, and should be regarded more as natural pertubations than as anthropogenic instability in the ecosystem." (Jakobsen & Ozhigin, 2011). However, when the

capelin stock has been depleted, intense exploitation by fisheries has been found to exacerbate the severity and duration of these lows.

Blanchet et al. (2019) argued that the presence of marine mammals in an ecosystem may make the food-web more robust and able to withstand bottom-up pertubations. Our result do not contradict their statement, but do show that, in the Barents Sea, the marine mammals and the fish species in our model were potentially competing for resources such as krill, copepods, amphipods and benthic organisms. Whether such resource competitions in the Barents Sea do contribute to the robustness of the food-web warrants further investigation.

Skern-Mauritzen et al. (2022) suggest that the potential for competition in the Greenland Sea is highest compared to that of the Iceland Sea and Barent Sea[2]. They provide two explanations for this: (I) the Greenland Sea is a more simple ecosystem that contains fewer interactions compared to the Iceland and Barents Seas and (II) the fisheries and marine mammals are more likely to have their target species overlap in the Greenland Sea, with the main target species being herring, blue whiting and mackerel. In our model, a higher potential for direct competition between marine mammals and fisheries in the Norwegian Sea is not predicted. Rather, the model suggests that direct competition over the past 35 years was more likely in the Barents Sea, with emphasis on other demersal fish as a shared resource (i.e., saithe, haddock, greenland halibut, golden redfish, and long rough dab). Furthermore, when considering the food-web mediated interactions that were previously mentioned, competitions are more probable within the Barents Sea.

Skern-Mauritzen et al. (2022) reported that, in the Greenland and Barents Seas, the average consumption by marine mammals is 4.5 times higher than the catch by fisheries between 2005-2015. This is similar to our finding that consumption by marine mammals is 5.2 times higher than removal by fisheries. However, when comparing the total annual consumption values, there is a considerable difference between the present study's estimation of 20 million tonnes per year and Skern-Mauritzen et al.'s (2022) estimation of 11.7 million tonnes per year. This can be accounted for by the difference in time-period that is used in Skern-Mauritzen et al. (2022). They do not provide a time-period over which their estimates are taken. Looking at the

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[2] 'The Greenland Sea' in Skern-Mauritzen et al. (2022) represents both the Greenland and Norwegian Sea areas.

cited literature on consumption by the marine mammals in that paper suggests that the time-period is from 2000 until 2019. Our annual consumption values are taken from all the trajectories spanning 35 years, from 1988 to 2021.

To put our results into perspective, other studies with different study areas can be compared for a similar marine mammal-fisheries interaction. Generally, there seems to be little evidence for a direct competition between marine mammals and fisheries and weak evidence for a food-web mediated competitive interaction (Kaschner & Pauly, 2005b; Morissette et al., 2010, 2012) In the Southern Ocean, the potential for direct and food-web mediated interaction is high between the marine mammals and krill fisheries (Costa & Crocker, 1996; May et al., 1979). In the Pacific Ocean, the evidence for direct competition between marine mammas and fisheries for prey is limited, but a food-web mediated competitive interaction may be present (Chasco et al., 2017; Fu et al., 2020; Trites et al., 1997). Within our model we see a similar pattern, with limited evidence for a direct competition between marine mammals and fisheries, together with possible food-web mediated competition.

5.3 Implications for conservation and fisheries management

The importance of marine mammals within ecosystems has been highlighted more frequently over the past few decades (Blanchet et al., 2019; W. Bowen, 1997; Corkeron, 2009). Marine mammals occupy more than just the role of top predator in large marine ecosystems. They maintain numerous direct trophic connections that connect them with over half of the species present in the Barents Sea, thus potentially contributing to the stability of the food-web. This is corroborated by the idea that high trophic level predators can enhance food-web stability when predating on multiple prey species, which is called frequency dependent prey selection (Allen et al., 1997; Blanchet et al., 2019; Gross et al., 2009). Furthermore, the present study outcomes show that marine mammals were major drivers in the Norwegian and Barents Sea ecosystem over the past 35 years. This should be considered in policy decisions regarding conservation and fisheries management.

Since the 1990s, policy changes have widely resulted in the formal implementation of ecosystem-based fisheries management (Bianchi et al., 2008; FAO, 2002; Pikitch et al., 2004). However, as a previous study concluded, only 24 out of 1200 investigated marine fish stocks were actually managed with ecosystem processes in mind (Skern-Mauritzen et al., 2016). The

present study offers additional support for incorporating an ecosystem-based fisheries management approach into a policy-making framework, not only for the management of fish stocks, but also for conservation purposes. We can see that, for both seas, there was a potential for competition for resources present in the model. These competitive interactions should be addressed when considering an ecosystem-based fisheries management approach, as competitions in the food-web could have implications for the sustainability of the fishing industry.

5.4 Model strengths and weaknesses

The unique aspect of this study is the CaN modelling approach, which utilises a mass-balance strategy similar to Ecopath with Ecosim, but with a key difference of employing data as model input by using linear inverse modelling. A fully-functional model samples the trajectories based on the data and constraints, rather than the reverse, where the data is used to check the model output. CaN model outputs are directly affected by the model inputs, which are highly flexible and can represent a wide range of ecological patterns, observations, and assumptions.

The methodology employed in this study enables one to make confident deductions regarding both the direct and food-web mediated interactions between marine mammals and fisheries, despite considerable uncertainties in consumption estimates. This can be attributed to the model's intrinsic design, which connects all components, thereby limiting one component through its interactions with other components. Thus, the trophic and non-trophic interactions can define the entire scope of the components, even in cases of insufficient information.

In CaN models, it is important to scrutinise the model inputs for their inherent ecological implications so that self-perpetuating output patterns are not derived. That is, the assertion of the presence of emerging ecological patterns is not feasible if the input data implicitly creates the occurrence of those ecological patterns. Thus, it is necessary to examine the inputs to verify the model outputs.

Part of the model evaluation is a standard sensitivity analysis (Saltelli et al., 2000). Unfortunately, because of a lack of time, a sensitivity analysis was not performed. The sensitivity analysis could be performed on this model by changing the model inputs within the range of uncertainty.

The model outputs were examined and validated by experts in their respective fields. Experts were also engaged in the development of constraints and construction of the food-web structure throughout the model-building process. This collaborative approach to modelling has the potential to be successful if multiple stakeholders are involved in the project. Although this modelling approach has not been employed in such a collaborative manner in the past, it may be used more extensively in the future.

The model presented in this study lacks seasonal and spatial explicitness, as there is a limited amount of information about the seasonal and spatial variations within the ecosystem. Consequently, the model cannot account for those variations within the ecosystem, which could have contributed to the observed annual variations. For instance, it does not account for the fact that Norwegian spring spawning herring migrate to the Norwegian coastline for shelter during the winter and are predated upon by minke whales, humpback whales, and orcas. The absence of spatial information could result in decreased predation pressure and different patterns of competition in our model. Skern-Mauritzen et al. (2022) argued that an additional type of interaction should be added to the three types of interactions primarily involving strong direct competition proposed by DeMaster et al. (2001). This type is a spatially constrained and concentrated interaction, as it could lead to strong direct competition.

Not all species in the model are as well-documented as others. This means that, for species where data is lacking, assumptions are used to fill the gaps. Some examples of this are: the dietary changes of marine mammals over time, the dietary changes of multiple fish species in the model (except cod), changes in polar cod biomass over time, and the residence time of migrating species within the Norwegian and Barents Seas and how this has changed over time.

5.5 Competition assessment

The interactions between two predators of shared prey in our study are defined as the correlation between their consumption. In this context, a negative correlation is considered as an indication of competition. Specifically, a stronger negative correlation indicates stronger evidence for competition. This is a key and novel method explored in this study, as we investigate how consumption/catch by one group has varied in relation to the consumption/catch by another.

This is by no means the only method for assessing competition. There are other methods of defining competition that have been used in scientific publications. Examples of how

competition has been defined by other publications are by dietary trophic overlap (Skern-Mauritzen et al., 2022b), Morisita's overlap index (Jung et al., 2015; Krebs, 1999; Morisita, 1961), overlap in the cumulative biomass-trophic level relationship (Link et al., 2015; Pranovi et al., 2014), and Beverton-Holt and derivatives (Beverton & Holt, 1957; Hart et al., 2018). In the task of detecting competition, there is no universally accepted method.

Other alternative methods could have been employed for detecting competitive interactions. For example, it is possible to compute dietary overlap between predator groups over time to be able to track competition changes over the past dynamics.

5.6 Future work

A sensitivity analysis is warranted on the model input parameters. This would be to evaluate the model's performance and robustness.

For future work on this CaN model a continued dialogue with experts can be used to explore the model outputs and ensure that they pass the sanity checks based on expert knowledge. Together with experts, data and knowledge on the distribution of migratory species within and outside of the model's geographical boundaries can be gathered. This would help to improve the accuracy of the model.

This model could become even more comprehensive given more time. The separation of Norwegian spring spawning herring adults and juveniles into two individual stocks is correct, but the non-trophic link connecting them is not explicitly accounted for in the model and could be beneficial for the model performance. Although the biomass trajectories of both stocks are accurately represented in the model, this could be improved in future work. Additionally, to enhance the robustness of the conclusions regarding interactions, it would be beneficial to incorporate trophospecies that are currently outside the model domain. This will enable a more comprehensive examination of their bottom-up control as prey. However, it should be noted that the incorporation of additional components into the model domain is a complex task, as there are always more possible dynamics to be considered. The implementation of too many components and dynamics could undermine the power of CaN models, which is simplicity.

Use of the model could be explored in the projection of future scenarios. This can be used to simulate future dynamics that are predicated upon current conservation goals and catch quotas.

6 Conclusion

This study used non-linear modelling to investigate the potential inter-species interactions and ecosystem dynamics. The results of this study suggest the following conclusions:

The available information used in this model about the Norwegian and Barents Sea ecosystem is compatible and can be used to provide a coherent reconstruction of the dynamics over the past 35 years. The potential dynamics investigated are direct competition and food-web mediated interactions. The model supports evidence for past direct interactions in the Norwegian Sea ecosystem between marine mammals and fisheries over the past 35 years, with little evidence for direct competition. The model also supports past direct interactions in the Barents Sea, where most interactions are characterised by a bottom-up trophic control. However, the direct interaction between marine mammals and fisheries in relation to other demersal fish (i.e., haddock, saithe, Greenland halibut, long rough dab, and golden redfish) indicates a weak competitive interaction. Furthermore, there is evidence for food-web mediated interactions in the Norwegian Sea within the model. However, these interactions show little to no evidence of competition. There is also evidence for food-web mediated interactions in the Barents Sea within the model. These dynamics are mostly dominated by capelin and show that food-web mediated competition is possible between marine mammals and all fish for their shared planktonic and benthic prey. Finally, a holistic view of both ecosystems over the past 35 years shows that, in the model, there is evidence for food-web mediated interactions between marine mammals and fisheries, characterised by a bottom-up trophic control and competitive interaction.

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8 Appendix

8.1 Appendix 1 – Input parameters

Components and input parameters of the model.

Component	Assimilation efficiency	Digestibility	Other Losses	Inertia	Satiation
	Inside the model domain				
HerringNS	0.9	0.9	2.28	0.64	12
BlueWhitingNS	0.9	0.9	2.8	0.85	9
MackerelNS	0.9	0.9	2.26	0.63	12
CodBS	0.8	0.9	1.14	0.28	3
PolarCodBS	0.8	0.9	3.2	1.21	8
HerringBS	0.84	0.9	2.55	0.85	7.9
CapelinBS	0.8	0.9	2.55	1.6	9.3
OtherDemersalBS	0.8	0.9	1.43	0.37	3.2
MinkeWhale	0.92	0	7.2	0.2	11.95
ToothedWhales	0.925	0	5.24	0.15	8.62
OtherBaleenWhales	0.92	0	4.37	0.12	7.22
Seals	0.885	0	17.59	0.18	30.66
	Outside the model domain				
KrillNS	0	0.9	0	0	0
KrillBS	0	0.9	0	0	0
AmphipodsBS	0	0.9	0	0	0
MesopelagicAndOtherNS	0	0.9	0	0	0
FMinkeWhale	0	0	0	0	0
FSeals	0	0	0	0	0
FDemersal	0	0	0	0	0

FPelagic	0	0	0	0	0
Birds		0	0	0	0
CopepodBS	0	0.9	0	0	0
BenthosBS	0	0.6	0	0	0
ZooPlanktonNS	0	0.9	0	0	0
OutsideResources	0	0.9	0	0	0
OutsidePredation	0	0	0	0	0

8.2 Appendix 2 – Species list

Full list of components and the species represented within each component.

Component	List of species
HerringNS	Norwegian spring spawning herring (*Clupea harengus*) - only adults
BlueWhitingNS	Blue whiting (*Micromesistius poutassou*) - only adults
MackerelNS	Atlantic mackerel (*Scomber scombrus*) - only adults
CodBS	Atlantic cod (Northeast Arctic cod) (*Gadus morhua*) - 3+ year
PolarCodBS	Polar cod (*Boreogadus saida*)
HerringBS	Norwegian spring spawning herring (*Clupea harengus*) - only juvenile
CapelinBS	Capelin (*Mallotus villosus*)
OtherDemersalBS	Haddock (*Melanogrammus aeglefinus*), Saithe (*Pollachius virens*), Long rough dab (*Hippoglossoides platessoides*), Greenland halibut (*Reinhardtius*

	hippoglossoides) - 45cm+, Golden redfish (*Sebastes norvegicus*)
MinkeWhale	Common minke whale (*Balaenoptera acutorostrata*)
ToothedWhales	Sperm whale (*Physeter macrocephalus*), Killer whale (*Orcinus orca*), Harbour porpoise (*Phocoena phocoena*), White sided dolphin (*Lagenorhynchus acutus*), White beaked dolphin (*Lagenorhynchus albirostris*), Narwhale (*Monodon monoceros*), Beluga whale (*Delphinapterus leucas*), Long-finned pilot whale (*Globicephala melas*), Northern bottlenose whale (*Hyperoodon ampullatus*)
OtherBaleenWhales	Fin whale (*Balaenoptera physalus*), Blue whale (*Balaenoptera musculus*), Bowhead whale (*Balaena mysticetus*), Sei whale (*Balaenoptera borealis*), Humpback whale (*Megaptera novaeangliae*)
Seals	Hooded seal (*Cystophora cristata*), Harp seal (*Pagophilus groenlandicus*), Ringed seal (*Pusa hispida*), Grey seal (*Halichoerus grypus*), Harbour seal (*Phoca vitulina*), Bearded seal (*Erignathus barbatus*), Walrus (*Odobenus rosmarus*)
KrillNS	*Meganyctiphaenes norvegica, Thysanoessa longicaudata, Thysanoessa inermis*
KrillBS	*Thysanoessa inermis, Thysanoessa raschii, Thysanoessa longicaudata, Meganyctiphanes norvegica,*
AmphipodsBS	*Themisto libellula, Themisto abyssorum, Themisto compressa, Gammarus wilkitzkii, Apherusa glacialis, Onismus nanseni, Onismus glacialis*

MesopelagicAndOtherNS	*Benthosema glaciale, Maurolicus müelleri, Gonatus fabricii, Arctozenus risso, Sebastes mentella, Gonatus steenstrupi*
FMinkeWhale	Minke whale hunting
FSeals	Seal hunting
FDemersal	Demersal fish fisheries
FPelagic	Pelagic fish fisheries
Birds	Northern fulmar (*Fulmarus glacialis*), Black-legged kittiwake (*Rissa tridactyla*), Glaceous gull (*Larus hyperboreus*), Herring Gull (*Larus argentatus*), Great Black-backed Gull (*Larus marinus*), Lesser Black-backed Gull (*Larus fuscus*), Common Gull (*Larus canus*), Arctic tern (*Sterna paradisaea*), Ivory gull (*Pagophila eburnean*), Little auk (*Alle alle*), Brunnich guillemot (*Uria lomvia*) , Common guillemot (*Uria aalge*), Razorbill (*Alca torda*), Atlantic puffin (*Fratercula arctica*), Great cormorant (*Phalacrocorax carbo*), European shag (*Phalacrocrax aristotelis*), Black guillemot (*Cepphus grylle*)
CopepodBS	*Calanus finmarchicus, Calanus hyperboreus, Metridia longa, Calanus glacialis, Oithona similis, Pseudocalanus spp., Oithona spp. and Microcalanus spp.*
BenthosBS	Northern shrimp (*Pandalus borealis*), Other Crangonidae, *Colus sabini, Buccinum hydrophanum, Chlamys islandica, Bathyarca glacialis*, Polychaeta indet, *Brada inhabilis*, Polynoidae indet, *Spiochaetopterus typicus*, Chaetognaths, Ctenophora, *Urasterias linckii, Pontaster*

	tenuispinus, *Icasterias panopla*, *Henricia* sp., *Ctenodiscus crispatus*, *Crossaster papposus*, *Heliometra glacialis*, *Gorgonocephalus arcticus*, *Ophiacantha bidentata*, *Ophiopholis aculeata*, *Ophiopleura borealis*, *Ophioscolex glacialis*, *Ophiura sarsi*, *Pagurus pubescens*, *Chionoecetes opilio*, *Hyas* sp., *Balanus* sp., *Saduria sabini*, *Lebbeus polaris*, *Pontophilus norvegicus*, *Sabinea septemcarinata*, *Sclerocrangon ferox*
ZooPlanktonNS	Ostracods, Chaetognaths, *Limacina* sp., Appendicularia, *Calanus finmarchicus*, *Calanus hyperboreus*, *Metridia longa*, *Oithona similis*
OutsideResources	Resources acquired outside the modelled area
OutsidePredation	Predation outside the modelled area

8.3 Appendix 3 – input parameters calculations

Additional information for the derivation of the model input parameters. This document is taken from Planque et al. (2022) and adjusted where necessary.

8.3.1 Input parameters for the final model

The derivation of biological parameters presented in this appendix was done following Lindstrøm *et al*. (2017) and adapted to the Norwegian and Barents Sea food-web.

8.3.1.1 Average individual weight used to derive parameters

For most model parameters, the species average individual weight is required. For herring, blue whiting, and mackerel we considered the mean weight of adult individuals. This was calculated using individual weight-at-age, numbers-at-age, and maturity-at-age available from stock assessments (ICES, 2022b, 2022c) using Eq.1. The marine mammals average weight was taken from Skern-Mauritzen et al. (2022) (Table 4).

$$\frac{\sum_{age} N_a \cdot W_a{}^2 \cdot M_a}{\sum_{age} N_a \cdot W_a \cdot M_a}$$

Where N_a is the number of fish of age a, W_a the mean weight of fish of age a and M_a the proportion of mature individual at age a.

Table 4, Average individual weights for individual species in the CaN model

Species or groups of species	Mean individual weight (kg)
HerringNS	$3.1 \cdot 10^{-1}$
BlueWhitingNS	$1.0 \cdot 10^{-1}$
MackerelNS	$3.3 \cdot 10^{-1}$
CodBS	6.2
PolarCodBS	$1.6 \cdot 10^{-2}$
HerringBS	$7.2 \cdot 10^{-2}$
CapelinBS	$1.3 \cdot 10^{-2}$
OtherDemersalBS	2.0
MinkeWhale	$6.6 \cdot 10^{3}$
ToothedWhales	$2.4 \cdot 10^{4}$
OtherBaleenWhales	$5.0 \cdot 10^{4}$
Seals	$1.8 \cdot 10^{2}$

8.3.1.2 Satiation

Satiation, σ (kg prey·kg predator^{-1}), is the maximum consumption per unit biomass of a predator per unit time. This indicates the maximum amount of biomass that can be consumed per unit biomass of that predator at each time step. Where a value of 3 indicates that the predator can eat 3 times their own biomass in prey biomass. The parameter values employed for the species included in this study were obtained from general theoretical formula from Yodzis & Innes (1992).

$$\sigma_{pt} = \frac{1}{\gamma_{pt}\kappa_{py}} f_J a_J M_{pt}^{-0.25}$$

M_{pt} is the average individual weight (kg) of a predator species pt, γ_{py} is its potential assimilation efficiency (see 1.1), κ_{py} is the digestibility correction factor of the prey py (see 1.2), f_J is a ecosystem specific fractional quantity, and a_J (kg·(kg·y^{-1})·kg$^{0.25}$) is the coefficient of allometric relationship between the maximum rate of metabolizable energy and the weight of the species (Yodzis and Innes, 1992).

Table 5, Input values of satiation for individual species included in the CaN model

Trophospecies	Wet weight (kg)	Potential assimilation efficiency γ (unitless)	Digestibility correction factor κ (unitless)	Fractional properties fj (unitless)	Coefficient of allometric relationship aj (kg(kg yr)-1 kg0.25)	Satiation (σ) (y-1)
HerringNS	3.1·10^{-1}	0.9	0.9	0.5	8.9	7.34
BlueWhitingNS	1.0·10^{-1}	0.9	0.9	0.5	8.9	9.77
MackerelNS	3.3·10^{-1}	0.9	0.9	0.5	8.9	7.26
CodBS	6.2	0.8	0.9	0.2	8.9	1.57
PolarCodBS	1.6·10^{-2}	0.8	0.9	0.2	8.9	6.92
HerringBS	7.2·10^{-2}	0.84	0.9	0.2	8.9	4.54
CapelinBS	1.3·10^{-2}	0.8	0.9	0.2	8.9	7.36
OtherDemersalBS	2.0	0.80	0.9	0.2	8.9	2.07
MinkeWhale	6.6·10^{3}	0.92	x	1	89.2	11.95
ToothedWhales	2.4·10^{4}	0.925	x	1	89.2	8.62
OtherBaleenWhales	5.0·10^{4}	0.92	x	1	89.2	7.22
Seals	1.8·10^{2}	0.89	x	1	89.2	30.66

8.3.1.3 Inertia

Inertia, α (y^{-1}), is the maximum change of biomass a component can have over a unit of time. Inertia is strictly positive and is given by e^{α}. With a given inertia of 1 the maximum rate of change is limited to e^{1} and e^{-1}, meaning a maximum change of 271% and 37% from the initial biomass (at time t). The inertia for each component was derived from allometric relationships (Savage et al., 2004a; R. J. Williams et al., 2007; Yodzis & Innes, 1992).

In Yodzis & Innes (1992) they suggested the equation to estimate the species' maximum growth rate (ρ_i) as followed.

8.3.1.3.1 From Yodzis and Innes (1992)

Initially, Yodzis & Innes (1992) suggested an equation (Eq.4, Table S2.4) to estimate the species maximum growth rate (ρ_i):

$$\rho_i = f_r a_r M_i^{-0,25}$$

Where M_i is the average individual weight (kg) of a species i, f_r a fractional quantity and a_r (kg·(kg·y^{-1})·kg$^{0.25}$) is the coefficient of allometric relationship between the maximum rate of metabolizable energy and the weight of the species.

Table 6, Inertia varlues for each species included in the CaN model, derived from Yodzis and Innes (1992)

Trophospecies	Wet weight (kg)	f_r	a_r (kg·(kg·y^{-1})·kg$^{0.25}$)	Inertia (α)
HerringNS	$3.1 \cdot 10^{-1}$	0.1	6.6	**0.88**
BlueWhitingNS	$1.0 \cdot 10^{-1}$	0.1	6.6	**1.17**
MackerelNS	$3.3 \cdot 10^{-1}$	0.1	6.6	**0.87**
CodBS	6.2	0.1	6.6	**0.42**
PolarCodBS	$1.6 \cdot 10^{-2}$	0.1	6.6	**1.85**
HerringBS	$7.2 \cdot 10^{-2}$	0.1	6.6	**1.27**
CapelinBS	$1.3 \cdot 10^{-2}$	0.1	6.6	**1.96**
OtherDemersalBS	2.0	0.1	6.6	**0.55**
MinkeWhale	$6.6 \cdot 10^{3}$	0.1	34.3	**0.38**
ToothedWhales	$2.4 \cdot 10^{4}$	0.1	34.3	**0.28**
OtherBaleenWhales	$5.0 \cdot 10^{4}$	0.1	34.3	**0.23**
Seals	$1.8 \cdot 10^{2}$	0.1	34.3	**0.94**

8.3.1.3.2 From Savage et al (2004)

Savage et al. (2004b) defined the daily maximal growth rate (r_{max}) of a species i as follows:

$$r_{max,i} = e^{a_{s,i}} e^{\frac{-b_{s,i}}{kT_i}} M_i^{-0.25}$$

Where M_i is the average individual weight (μg) of species i, a_s and b_s are the species-specific coefficients derived from Savage et al. (2004b), a_s is the coefficient and b_s is the intercept of the relationship of mass-corrected exponential population growth multiplied by $M^{0.25}$ to inverse max temperature, k is the Boltzmann constant ($k = 8.62.10^{-5}$ eV.K^{-1}), and T_i is the body temperature (in Kelvin) of the organism considered. The latter is set to the average water temperature the species resides in.

The daily maximum growth rate (r_{max}) is converted into the annual maximum growth rate (inertia, ρ) by multiplying by the number of days, d_i, corresponding to the time-period during which individuals of the considered species grow in a year. Also, the values of d_i depends on the environmental conditions.

$$\rho_i = r_{max,i} \cdot d_i$$

Table 7, Inertia values for each species included in the CaN model, derived from Savage et al (2004).

Trophospecies	Wet weight (μg)	Temperature (K)	a_s	b_s	Boltzmann (eV. K^{-1})	d (days)	**Inertia (α)**
HerringNS	$3.1 \cdot 10^8$	280	12.57	0.35	$8.62 \cdot 10^{-5}$	365	**0.40**
BlueWhitingNS	$1.0 \cdot 10^8$	280	12.57	0.35	$8.62 \cdot 10^{-5}$	365	**0.53**
MackerelNS	$3.3 \cdot 10^8$	280	12.57	0.35	$8.62 \cdot 10^{-5}$	365	**0.39**
CodBS	$6.2 \cdot 10^9$	275	12.57	0.35	$8.62 \cdot 10^{-5}$	365	**0.14**
PolarCodBS	$1.6 \cdot 10^7$	273.15	12.57	0.35	$8.62 \cdot 10^{-5}$	365	**0.58**
HerringBS	$7.2 \cdot 10^7$	274.15	12.57	0.35	$8.62 \cdot 10^{-5}$	365	**0.42**
CapelinBS	$1.3 \cdot 10^7$	280	12.57	0.35	$8.62 \cdot 10^{-5}$	365	**0.88**
OtherDemersalBS	$2.0 \cdot 10^9$	275	12.57	0.35	$8.62 \cdot 10^{-5}$	365	**0.19**
MinkeWhale	$6.6 \cdot 10^{12}$	278.15	12.57	0.35	$8.62 \cdot 10^{-5}$	180	**0.01**
ToothedWhales	$2.4 \cdot 10^{13}$	278.15	12.57	0.35	$8.62 \cdot 10^{-5}$	364	**0.02**
OtherBaleenWhales	$5.0 \cdot 10^{13}$	278.15	12.57	0.35	$8.62 \cdot 10^{-5}$	182	**0.01**
Seals	$1.77 \cdot 10^{11}$	278.15	12.57	0.35	$8.62 \cdot 10^{-5}$	365	**0.07**

The species inertia values used to parametrize the CaN model for the Norwegian and Barents Seas, were calculated as the arithmetic mean ($\bar{\rho}$) of both species' inertia estimates from the Savage *et al*. (2004) and Yodzis and Innes (1992) (Table 8).

Table 8. Arithmetic mean of inertia calculated from Savage et al (2004) and Yodzis and Innes (1992) and included in the Norwegian sea CaN model

Trophospecies	ρ_{Savage}	$\rho_{Yodzis \, and \, Innes}$	$\bar{\rho}$
HerringNS	0.40	0.88	**0.64**
BlueWhitingNS	0.53	1.17	**0.85**
MackerelNS	0.39	0.87	**0.63**
CodBS	0.14	0.42	**0.28**
PolarCodBS	0.58	1.85	**1.21**
HerringBS	0.42	1.27	**0.85**
CapelinBS	0.88	1.96	**1.42**
OtherDemersalBS	0.19	0.55	**0.37**
MinkeWhale	0.01	0.38	**0.20**
ToothedWhales	0.02	0.28	**0.15**
OtherBaleenWhales	0.01	0.23	**0.12**
Seals	0.07	0.94	**0.51**

8.3.1.4   Other losses

Other losses, μ (y^{-1}), is the mortality coefficient that accounts for losses, such as metabolic losses and mortality not explicitly accounted for within the model. It is assumed to be equal to the field metabolic rate (FMR) of a species, which is estimated at three times the basal metabolic rate (BMR) (Speakman & Selman, 2003). They are expressed as $e^{-\mu}$, making the term strictly positive. In practice, the other losses indicate that with a value of 1, e^{-1}, that after one time unit the biomass is 36% of the initial biomass, equivalent to 0.27% daily loss.

Species' other losses are calculated using two different calculations, applying to all the components and two other calculations applying to only a set. Overall, each component's other losses parameter is derived from three separate equations.

8.3.1.4.1   Yodzis & Innes (1992)

Starting with Yodzis & Innes (1992), they suggested an estimation equation for FMR.

$$\mu_i = a_T M_i^{-0,25}$$

Where Mi is the average individual weight (kg) of the species i and a_T (kg(kg year-1)kg0.25) a constant that is animal group specific.

Trophospecies	Wet weight (kg)	a_T (kg·(kg·y^{-1})·kg$^{0.25}$)	Other losses (μ)
HerringNS	$3.1 \cdot 10^{-1}$	2.3	**3.07**
BlueWhitingNS	$1.0 \cdot 10^{-1}$	2.3	**4.09**
MackerelNS	$3.3 \cdot 10^{-1}$	2.3	**3.04**
CodBS	6.2	2.3	**1.46**
PolarCodBS	$1.6 \cdot 10^{-2}$	2.3	**6.44**
HerringBS	$7.2 \cdot 10^{-2}$	2.3	**4.44**
CapelinBS	$1.3 \cdot 10^{-2}$	2.3	**6.85**
OtherDemersalBS	2.0	2.3	**1.93**
MinkeWhale	$6.6 \cdot 10^{3}$	54.9	**6.09**
ToothedWhales	$2.4 \cdot 10^{4}$	54.9	**4.42**
OtherBaleenWhales	$5.0 \cdot 10^{4}$	54.9	**3.68**
Seals	$1.8 \cdot 10^{2}$	54.9	**15.04**

8.3.1.4.2   Gillooly et al. (2001)

Lindstrøm et al. (2017) calculated a FMR in Joule min^{-1} using Gillooly et al. (2001), which suggested a daily FMR. Afterwards the species FMR is converted to kg kg^{-1} year^{-1} using .

$$\mu_i = 3\left(e^{a_{bmr}}e^{\frac{-b_{bmr}\cdot 1000}{T}}M_i^{0,75}\right)$$

Table 9, Other losses generated by Gillooly et al. (2001)

Trophospecies	Wet weight (g)	Temperature (K)	a_{bmr}	b_{bmr}	Losses (J/min)	BMR (kg/(kg/y)	**Other losses (μ)**
HerringNS	$3.1 \cdot 10^{2}$	280	14.47	5.02	2.34	0.56	**1.69**
BlueWhitingNS	$1.0 \cdot 10^{2}$	280	14.47	5.02	$9.96 \cdot 10^{-1}$	0.75	**2.24**
MackerelNS	$3.3 \cdot 10^{2}$	280	14.47	5.02	2.42	0.56	**1.67**

CodBS	$6.2 \cdot 10^2$	275	14.47	5.02	$1.58 \cdot 10^1$	0.19	**0.58**
PolarCodBS	$1.6 \cdot 10^{-2}$	273.15	14.47	5.02	$1.63 \cdot 10^{-1}$	0.75	**2.25**
HerringBS	$7.2 \cdot 10^{-2}$	274.15	14.47	5.02	$5.31 \cdot 10^{-1}$	0.55	**1.66**
CapelinBS	$1.3 \cdot 10^{-2}$	280	14.47	5.02	$1.45 \cdot 10^{-1}$	0.85	**2.56**
OtherDemersalBS	2.0	275	14.47	5.02	6.91	0.25	**0.76**
MinkeWhale	$6.6 \cdot 10^3$	278.15	29.49	9.1	$1.51 \cdot 10^5$	1.72	**5.16**
ToothedWhales	$2.4 \cdot 10^4$	278.15	29.49	9.1	$3.97 \cdot 10^5$	1.25	**3.74**
OtherBaleenWhales	$5.0 \cdot 10^4$	278.15	29.49	9.1	$6.86 \cdot 10^5$	1.04	**3.12**
Seals	$1.8 \cdot 10^2$	278.15	29.49	9.1	$1.01 \cdot 10^4$	4.25	**12.74**

Where M_i is the average individual weight (g) of the species i, a_{bmr} and b_{bmr} are taxa specific constants taken from Gillooly et al. (2001), and T is the body temperature of the species i (in Kelvin).

$$FMR_k = \frac{FMR_J \cdot 1440 \cdot d_i}{7 \cdot 10^6 \cdot M_i}$$

Conversion from daily field metabolic rate in Joule min^{-1} to kg kg^{-1} year^{-1}. With the M_i is the average individual weight (kg) of the species i, the FMR_j the field metabolic rate in Joule min^{-1}, and d_i the corresponding growth period of the species i. The 1440 corresponds to the number of minutes during the day with the $7 \cdot 10^6$ corresponding to the assumption that 1kg of wet mass corresponds to $7 \cdot 10^6$ Joule (Peters, 1983).

8.3.1.4.3   *Makarieva et al. (2008)*

The third method is described by Makarieva et al. (2008), that describes the average metabolic rates (AMR$_{MAK}$, W·kg^{-1}) of numerous species and taxa. This method was used only to calculate the FMR for the fish species within the model. The equation looks as follows.

$$\mu_i = \frac{AMR_{MAK} \cdot 86400 \cdot d_i}{7 \cdot 10^6}$$

Where AMR$_{MAK}$ is the species AMR derived by Makarieva et al., (2008) expressed in Joule s^{-1} kg^{-1}. With this equation that rate is converted to kg kg^{-1} year^{-1} using 86400 describing the number of seconds in a day and d_i the number of days species i grows during a year. $7 \cdot 10^6$

corresponds to the conversion of Joule to wet mass, where 1kg of wet mass corresponds to $7\cdot10^6$ Joule (Peters, 1983).

Trophospecies	q25Wkg	Q10	Tamb	qAmbWkg	BMR: Losses (kg/(kg/year))	FMR: Losses (kg/(kg/year))
HerringNS	0.38	1.65	7	0.15	0.70	2.09
BlueWhitingNS	0.38	1.65	7	0.15	0.70	2.09
MackerelNS	0.38	1.65	7	0.154	0.70	2.09
CodBS	0.328	1.65	1.85	0.10	0.46	1.39
PolarCodBS	0.233	1.65	0	0.067	0.30	0.90
HerringBS	0.38	1.65	1	0.11	0.51	1.54
CapelinBS	0.38	1.65	1	0.11	0.51	1.54
OtherDemersalBS	0.38	1.65	1.90	0.12	0.54	1.61

8.3.1.4.4   *T. M. Williams et al. (2004)*

The last method is only used for the other losses of the marine mammal groups. This method is described by T. M. Williams et al. (2004) and describes a FMR in Joule per second using the following equation.

$$FMR_b = 19.65 M_b{}^{0.756}$$

Where the M_b is the species individual body weight in kilograms.

This FMR in Joule per second was afterwards converted to kg kg^{-1} year^{-1}. The arithmetic mean ($\bar{\mu}$) of the estimates was calculated for all components.

Trophospecies	Wet weight (kg)	Joule/second	Losses (kg/year)	**FMR: Losses (kg/(kg/year))**
MinkeWhale	$6.6\cdot10^3$	$1.52\cdot10^4$	$6.8\cdot10^5$	**10.35**
ToothedWhales	$2.4\cdot10^4$	$4.01\cdot10^4$	$1.8\cdot10^5$	**7.57**

OtherBaleenWhales	$5.0 \cdot 10^4$	$6.97 \cdot 10^4$	$3.1 \cdot 10^5$	**6.33**
Seals	$1.8 \cdot 10^2$	$9.87 \cdot 10^2$	$4.4 \cdot 10^3$	**25.01**

8.4 Appendix 4 – Constraints documentation

In the model, in the observations.

The Row refers to the row the constraint is in on the XLSX file for the model input.

8.4.1 Fish biomass

8.4.1.1 Norwegian spring spawning herring

Row	Name	Constraints	Time-period	Description	References
2.	CHerringNSHigh	The biomass of herring in the Norwegian Sea is at most the upper bound of the estimated biomass (stock).	1988:2021	We assume that the biomass of herring cannot exceed the upper bound (confidence interval of 99%) of stock estimation for a given year.	**ICES 2021 WGWIDE table 4.5.1.4** We have annual stock estimates with 95% confidence interval. We calculated the standard deviation for each year and used that to calculate the 99% confidence interval.
3.	CHerringNSLow	The biomass of herring in the Norwegian Sea is at least the lower bound of the estimated biomass (stock).	1988:2021	We assume that the biomass of herring cannot exceed the lower bound (confidence interval of 99%) of stock estimation for a given year.	**ICES 2021 WGWIDE table 4.5.1.4** We have annual stock estimates with 95% confidence interval. We calculated the standard deviation for each year and used that to calculate the 99% confidence interval.

8.4.1.2 Blue whiting

4.	CBlueWhitingHigh	The biomass of blue whiting in the Norwegian Sea is at most the upper bound of the estimated biomass (stock).	**1988:2021**	We assume that the biomass of herring cannot exceed the upper bound (confidence interval of 99%) of stock estimation for a given year.	**ICES 2021 WGWIDE table 2.4.1.5** We have annual stock estimates with 95% confidence interval. We calculated the standard deviation for each year and used that to calculate the 99% confidence interval.
5.	CBlueWhitingLow	The biomass of blue whiting in the Norwegian Sea is at least the lower bound of the estimated biomass (stock).	**1988:2021**	We assume that the biomass of blue whiting cannot exceed the lower bound (confidence interval of 99%) of stock estimation for a given year.	**ICES 2021 WGWIDE table 2.4.1.5** We have annual stock estimates with 95% confidence interval. We calculated the standard deviation for each year and used that to calculate the 99% confidence interval.

8.4.1.3 Atlantic mackerel

6.	CMackerelHigh	The biomass of mackerel in the Norwegian Sea is at most the upper bound of the estimated biomass (stock).	**1988:2021**	We assume that the biomass of herring cannot exceed the upper bound (confidence interval of 99%) of stock estimation for a given year.	**ICES 2022 Stock assessment graphs (assessment key: 17509)** We have annual stock estimates with 95% confidence interval. We calculated the standard deviation for each year and used that to calculate the 99% confidence interval.
7.	CMackerelLow	The biomass of mackerel in the Norwegian Sea is at least the lower bound of the estimated biomass (stock).	**1988:2021**	We assume that the biomass of blue whiting cannot exceed the lower bound (confidence interval of 99%) of stock estimation for a given year.	**ICES 2022 Stock assessment graphs (assessment key: 17509)** We have annual stock estimates with 95% confidence interval. We calculated the

					standard deviation for each year and used that to calculate the 99% confidence interval.

8.4.1.4 Altantic cod

8.	CCodHigh	The biomass of cod in the Barents Sea is at most the lower bound of the estimated biomass (stock) with 120% uncertainty.	1988:2021	We assume that the biomass of cod cannot exceed the upper bound (TSB*1.2) of stock estimation for a given year.	**JNR_AFWG 2022 Table 3.18** We have annual stock biomass estimates. We use this with an uncertainty of 120% as the upper limit.
9.	CCodLow	The biomass of cod in the Norwegian Sea is at least the lower bound of the estimated biomass (stock) with 120% uncertainty.	1988:2021	We assume that the biomass of cod cannot exceed the lower bound (TSB/1.2) of stock estimation for a given year.	**JNR_AFWG 2022 Table 3.18** We have annual stock biomass estimates. We use this with an uncertainty of 120% as the lower limit.

8.4.1.5 Polar cod

10.	CPolarCodHigh	The biomass of polar cod in the Barents Sea is at most the lower bound of the estimated biomass (stock) with 400% uncertainty.	1988:2017, 2020:2021	We assume that the biomass of polar cod cannot exceed the upper bound (TSB*4) of stock estimation for a given year.	**ICES 2021 WGIBAR Figure A5.65** We have annual stock biomass estimates. We use this with an uncertainty of 400% as the upper limit.
11.	CPolarCodLow	The biomass of polar cod in the Barents Sea is at least	1988:2021	We assume that the biomass of polar cod cannot exceed the lower bound	**ICES 2021 WGIBAR Figure A5.65**

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		the lower bound of the estimated biomass (stock) with 120% uncertainty.		(TSB/1.5) of stock estimation for a given year.	We have annual stock biomass estimates. We use this with an uncertainty of 120% as the lower limit.

8.4.1.6 Capelin

12.	CCapelinHigh	The biomass of capelin in the Barents Sea is at most the upper bound of the estimated biomass (stock) with 150% uncertainty.	**1988:2004, 2006:2015, 2017:2021**	We assume that the biomass of capelin cannot exceed the upper bound (TSB/1.5) of stock estimation for a given year.	**ICES 2021 AFWG Table 10.5** We have annual stock biomass estimates. We use this with an uncertainty of 150% as the upper limit.
13.	CCapelinLow	The biomass of capelin in the Barents Sea is at least the lower bound of the estimated biomass (stock) with 150% uncertainty.	**1988:2021**	We assume that the biomass of capelin cannot exceed the lower bound (TSB/1.5) of stock estimation for a given year.	**ICES 2021 AFWG Table 10.5** We have annual stock biomass estimates. We use this with an uncertainty of 150% as the lower limit.

8.4.1.7 Juvenile herring

14.	CHerringBSHigh	The biomass of juvenile herring in the Barents Sea is at most the lower bound of the estimated biomass	**1988:2021**	We assume that the biomass juvenile herring cannot exceed the upper bound	**ICES 2021 WGIBAR Figure A5.62 (1+2-year group)**

		(stock) with 150% uncertainty.		(("1,2,3year" group biomass) *4) of stock estimation for a given year.	**ICES 2021 WGWIDE Table 4.5.1.2 (3-year group abundance)** **ICES 2021 WGWIDE Table 4.4.4.2 (3-year group weight at age in stock)** We have annual biomass estimates of the 1+2-year group and 3-year group. We use this with an uncertainty of 150% as the upper limit.
15.	CHerringBSLow	The biomass of juvenile herring in the Barents Sea is at least the lower bound of the estimated biomass (stock) with 150% uncertainty.	1988:2021	We assume that the biomass of juvenile herring cannot exceed the lower bound (("1,2,3year" group biomass) /1.5) of stock estimation for a given year.	**ICES 2021 WGIBAR Figure A5.62 (1+2-year group)** **ICES 2021 WGWIDE Table 4.5.1.2 (3-year group abundance)** **ICES 2021 WGWIDE Table 4.4.4.2 (3-year group weight at age in stock)** We have annual biomass estimates of the 1+2-year group and 3-year group. We use this with an uncertainty of 150% as the lower limit.

8.4.1.8 Other demersal fish

| 16. | COtherDemersal High | The biomass of other demersal fish in the Barents Sea is at most the upper bound of the estimated biomasses (stock) from the different species. | 1988:2021 | We assume that the biomass of herring cannot exceed the upper bound (SSB with confidence interval of 99% + SSB*1.2 and SSB*SSB) of stock estimation for a given year. The difference between SSB*1.5 and 1.2 is to account for uncertainty in the type of assessment. | **Saithe: ICES 2021 AFWG summarised in STOCK ASSESSMENT GRAPHS** We have annual stock estimates with 95% confidence interval (SSB). We calculated the standard deviation for each year and used that to calculate the 99% confidence interval.

 Haddock: ICES 2021 AFWG summarised in STOCK ASSESSMENT GRAPHS We have annual stock estimates with 95% confidence interval (SSB). We calculated the standard deviation for each year and used that to calculate the 99% confidence interval.

 Greenland halibut: ICES 2021 AFWG summarised in STOCK ASSESSMENT GRAPHS We have annual stock estimates of 45cm+ (SSB). We use this with an uncertainty of 120% as the upper limit.

 Golden redfish: ICES 2021 AFWG summarised in STOCK ASSESSMENT |

					GRAPHS We have annual stock estimates of (SSB). We use this with an uncertainty of 120% as the upper limit. **Long rough dab: ICES 2021 WGIBAR Figure A5.84** We have annual stock estimates of (SSB). We use this with an uncertainty of 150% as the upper limit.
17.	COtherDemersal Low	The biomass of other demersal fish in the Barents Sea is at least the lower bound of the estimated biomass (stock) from the different species.	1988:2021	We assume that the biomass of herring cannot exceed the lower bound (confidence interval of 99% + SSB*1.2 and SSB*SSB) of stock estimation for a given year. The difference between SSB*1.5 and 1.2 is to account for uncertainty in the type of assessment.	**Saithe: ICES 2021 AFWG summarised in STOCK ASSESSMENT GRAPHS** We have annual stock estimates with 95% confidence interval (SSB). We calculated the standard deviation for each year and used that to calculate the 99% confidence interval. **Haddock: ICES 2021 AFWG summarised in STOCK ASSESSMENT GRAPHS** We have annual stock estimates with 95% confidence interval (SSB). We calculated the

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					standard deviation for each year and used that to calculate the 99% confidence interval.
					Greenland halibut: ICES 2021 AFWG summarised in [STOCK ASSESSMENT GRAPHS](#) We have annual stock estimates of 45cm+ (SSB). We use this with an uncertainty of 120% as the lower limit.
					Golden redfish: ICES 2021 AFWG summarised in [STOCK ASSESSMENT GRAPHS](#) We have annual stock estimates of (SSB). We use this with an uncertainty of 120% as the lower limit.
					Long rough dab: ICES 2021 WGIBAR Figure A5.84 We have annual stock estimates of (SSB). We use this with an uncertainty of 150% as the lower limit.

8.4.2 Marine mammals' biomass

8.4.2.1 Minke whale

Row	Name	Constraints	Time-period	Description	References
18.	cMinkeWhaleHigh	The biomass of minke whale is at most the upper bound of the estimated biomass (stock).	1988:2021	We assume that the biomass of minke whale cannot exceed the upper bound (confidence interval of 95%) of the mean stock upper limit.	**Skern-Mauritzen et al., 2022** We have a mean stock estimate with 95% confidence interval. We calculate the 99% CI. We use that as the upper limit for the years where our data is lacking.
19.	cMinkeWhaleLow	The biomass of minke whale is at least the lower bound of the estimated biomass (stock).	1988:2021	We assume that the biomass of minke whale cannot exceed the upper bound (confidence interval of 95%) of the mean stock lower limit.	**Skern-Mauritzen et al., 2022** We have a mean stock estimate with 95% confidence interval. We calculate the 99% CI. We use that as the lower limit for the years where our data is lacking.
20.	cMinkeWhale88_89 High	The mean biomass of minke whale for 1988:1989 is at most the upper bound of the estimated mean biomass in 1988:1989 (stock) with 120% uncertainty.	1988:1989	We assume the mean biomass of minke whale in 1988:1989 cannot exceed the upper bound of the mean biomass for 1988:1989 with an uncertainty of 120%.	**Lindstrøm calculation** We have mean stock biomass estimate for 1988:1989. We use this with an uncertainty of 120% as the upper limit.

21.	cMinkeWhale88_89 Low	The mean biomass of minke whale for 1988:1989 is at least the lower bound of the estimated mean biomass in 1988:1989 (stock) with 120% uncertainty.	**1988:1989**	We assume the mean biomass of minke whale in 1988:1989 cannot exceed the lower bound of the mean biomass for 1988:1989 with an uncertainty of 120%.	**Lindstrøm calculation** We have mean stock biomass estimate for 1988:1989. We use this with an uncertainty of 120% as the lower limit.
22.	cMinkeWhale95High	The mean biomass of minke whale for 1995 is at most the upper bound of the estimated mean biomass in 1995 (stock) with 120% uncertainty.	**1995**	We assume the biomass of minke whale in 1995 cannot exceed the upper bound of the mean biomass for 1995 with an uncertainty of 120%.	**Lindstrøm calculation** We have stock biomass estimate for 1995. We use this with an uncertainty of 120% as the upper limit.
23.	cMinkeWhale95Low	The mean biomass of minke whale for 1995 is at least the lower bound of the estimated mean biomass in 1995 (stock) with 120% uncertainty.	**1995**	We assume the biomass of minke whale in 1995 cannot exceed the lower bound of the mean biomass for 1995 with an uncertainty of 120%.	**Lindstrøm calculation** We have stock biomass estimate for 1995. We use this with an uncertainty of 120% as the lower limit
24.	cMinkeWhale96_01 High	The mean biomass of minke whale for 1996:2001 is at most the upper bound of the estimated mean biomass in 1996:2001 (stock) with 120% uncertainty.	**1996 :2001**	We assume the mean biomass of minke whale in 1996:2001 cannot exceed the upper bound of the mean biomass for 1996:2001 with an uncertainty of 120%.	**Lindstrøm calculation** We have mean stock biomass estimate for 1996:2001. We use this with an uncertainty of 120% as the upper limit

25.	cMinkeWhale96_01 Low	The mean biomass of minke whale for 1996:2001 is at least the lower bound of the estimated mean biomass in 1996:2001 (stock) with 120% uncertainty.	1996 :2001	We assume the mean biomass of minke whale in 1996:2001 cannot exceed the lower bound of the mean biomass for 1996:2001 with an uncertainty of 120%.	**Lindstrøm calculation** We have mean stock biomass estimate for 1996:2001. We use this with an uncertainty of 120% as the lower limit
26.	cMinkeWhale 02-07High	The mean biomass of minke whale for 2002:2007 is at most the upper bound of the estimated mean biomass in 2002:2007 (stock) with 120% uncertainty.	2002:2007	We assume the mean biomass of minke whale in 2002:2007 cannot exceed the upper bound of the mean biomass for 2002:2007 with an uncertainty of 120%.	**Lindstrøm calculation** We have mean stock biomass estimate for 2002:2007. We use this with an uncertainty of 120% as the upper limit
27.	cMinkeWhale 02-07Low	The mean biomass of minke whale for 2002:2007 is at least the lower bound of the estimated mean biomass in 2002:2007 (stock) with 120% uncertainty.	2002:2007	We assume the mean biomass of minke whale in 2002:2007 cannot exceed the lower bound of the mean biomass for 2002:2007 with an uncertainty of 120%.	**Lindstrøm calculation** We have mean stock biomass estimate for 2002:2007. We use this with an uncertainty of 120% as the lower limit
28.	cMinkeWhale 08-13High	The mean biomass of minke whale for 2008:2013 is at most the mean biomass in 2008:2013 (stock) with 120% uncertainty.	2008:2013	We assume the mean biomass of minke whale in 2008:2013 cannot exceed the upper bound of the mean biomass for 2008:2013 with an uncertainty of 120%.	**Lindstrøm calculation** We have mean stock biomass estimate for 2008:2013. We use this with an uncertainty of 120% as the upper limit

29.	cMinkeWhale 08-13Low	The mean biomass of minke whale for 2008:2013 is at least the lower bound of the estimated mean biomass in 2008:2013 (stock) with 120% uncertainty.	**2008:2013**	We assume the mean biomass of minke whale in 2008:2013 cannot exceed the lower bound of the mean biomass for 2008:2013 with an uncertainty of 120%.	**Lindstrøm calculation** We have mean stock biomass estimate for 2008:2013. We use this with an uncertainty of 120% as the lower limit
30.	cMinkeWhale 14-19High	The mean biomass of minke whale for 2014:2019 is at most the upper bound of the estimated mean biomass in 2014:2019 (stock with 120% uncertainty).	**2014:2019**	We assume the mean biomass of minke whale in 2014:2019 cannot exceed the upper bound of the mean biomass for 2014:2019 with an uncertainty of 120%.	**Lindstrøm calculation** We have mean stock biomass estimate for 2014:2019. We use this with an uncertainty of 120% as the upper limit
31.	cMinkeWhale 14-19Low	The mean biomass of minke whale for 2014:2019 is at least the lower bound of the estimated mean biomass in 2014:2019 (stock) with 120% uncertainty.	**2014:2019**	We assume the mean biomass of minke whale in 2014:2019 cannot exceed the lower bound of the mean biomass for 2014:2019 with an uncertainty of 120%.	**Lindstrøm calculation** We have mean stock biomass estimate for 2014:2019. We use this with an uncertainty of 120% as the lower limit

8.4.2.2 Toothed whales

32.	cToothedWhaleHigh	The biomass of toothed whales is at most the upper	**1988:2021**	We assume that the biomass of toothed whales cannot exceed the upper bound	**Skern-Mauritzen et al., 2022**

		bound of the estimated biomass (stock).		(confidence interval of 95%) of the mean stock upper limit.	We have a mean stock estimate with 95% confidence interval. We calculate the 99% CI. We use that as the upper limit for the years where our data is lacking. Each species within the toothed whales has their own 99% confidence interval. Those were summed to achieve the total.
33.	cToothedWhaleLow	The biomass of toothed whales is at least the lower bound of the estimated biomass (stock).	1988:2021	We assume that the biomass of the toothed whales cannot exceed the upper bound (confidence interval of 95%) of the mean stock lower limit.	**Skern-Mauritzen et al., 2022** We have a mean stock estimate with 95% confidence interval. We calculate the 99% CI. We use that as the lower limit for the years where our data is lacking. Each species within the toothed whales has their own 99% confidence interval. Those were summed to achieve the total.
34.	CTW02_07High	The upper mean biomass of toothed whales for 2002:2007 is at most the upper bound of the estimated mean biomass in 2002:2007 (stock).	2002:2007	We assume the biomass of fin- and humpback whale drives the overall dynamics of the other baleen whales and the mean stock biomass with 95% confidence interval (**Leonard & Øien., 2019**) is used as a lower bound with the addition of the other species mean over time upper limit (confidence interval of 95%)(**Skern-Mauritzen et al., 2022).**	**Leonard & Øien (2019)** We have mean stock biomass estimate with 95% confidence interval for 2002:2007 for killer-, sperm whale, harbour porpoise and white sided dolphin. We use the 95% CI as the upper limit. **Skern-Mauritzen et al., 2022**

					We have a mean stock estimate with 95% confidence interval. We use that as the upper limit. Each species within the other baleen whales has their own 95% confidence interval. Those were summed (except killer-, sperm whale, harbour porpoise and white sided dolphin) to achieve the total.
35.	CTW02_07Low	The lower mean biomass of toothed whales for 2002:2007 is at least the lower bound of the estimated mean biomass in 2002:2007 (stock).	2002:2007	We assume the biomass of fin- and humpback whale drives the overall dynamics of the other baleen whales and the mean stock biomass with 95% confidence interval (**Leonard & Øien., 2019**) is used as a lower bound with the addition of the other species mean over time lower limit (confidence interval of 95%)(**Skern-Mauritzen et al., 2022).**	**Leonard & Øien (2019)** We have mean stock biomass estimate with 95% confidence interval for 2002:2007 for killer-, sperm whale, harbour porpoise and white sided dolphin. We use the 95% CI as the lower limit. **Skern-Mauritzen et al., 2022** We have a mean stock estimate with 95% confidence interval. We use that as the lower limit. Each species within the other baleen whales has their own 95% confidence interval. Those were summed (except killer-, sperm whale, harbour porpoise and white sided dolphin) to achieve the total.

| 36. | CTW08_13High | The upper mean biomass of toothed whales for 2008:2013 is at most the upper bound of the estimated mean biomass in 2008:2013 (stock). | 2008:2013 | We assume the biomass of fin- and humpback whale drives the overall dynamics of the other baleen whales and the mean stock biomass with 95% confidence interval (**Leonard & Øien., 2019**) is used as a upper bound with the addition of the other species mean over time lower limit (confidence interval of 95%)(**Skern-Mauritzen et al., 2022**). | **Leonard & Øien (2019)**

We have mean stock biomass estimate with 95% confidence interval for 2008:2013 for killer-, sperm whale, harbour porpoise and white sided dolphin. We use the 95% CI as the upper limit.

Skern-Mauritzen et al., 2022

We have a mean stock estimate with 95% confidence interval. We use that as the upper limit.

Each species within the other baleen whales has their own 95% confidence interval. Those were summed (except killer-, sperm whale, harbour porpoise and white sided dolphin) to achieve the total. |
| 37. | CTW08_13Low | The lower mean biomass of toothed whales for 2008:2013 is at least the lower bound of the estimated mean biomass in 2008:2013 (stock). | 2008:2013 | We assume the biomass of fin- and humpback whale drives the overall dynamics of the other baleen whales and the mean stock biomass with 95% confidence interval (**Leonard & Øien., 2019**) is used as a lower bound with the addition of the other species mean over time lower limit (confidence interval of 95%)(**Skern-Mauritzen et al., 2022**). | **Leonard & Øien (2019)**

We have mean stock biomass estimate with 95% confidence interval for 2008:2013 for killer-, sperm whale, harbour porpoise and white sided dolphin. We use the 95% CI as the lower limit.

Skern-Mauritzen et al., 2022 |

					We have a mean stock estimate with 95% confidence interval. We use that as the lower limit. Each species within the other baleen whales has their own 95% confidence interval. Those were summed (except killer-, sperm whale, harbour porpoise and white sided dolphin) to achieve the total.
38.	CTW14_18High	The mean biomass of toothed whales for 2014:2018 is at most the upper bound of the estimated mean biomass in 2014:2018 (stock).	2014:2018	We assume the biomass of fin- and humpback whale drives the overall dynamics of the other baleen whales and the mean stock biomass with 95% confidence interval (**Leonard & Øien., 2019**) is used as a upper bound with the addition of the other species mean over time lower limit (confidence interval of 95%)(**Skern-Mauritzen et al., 2022**).	**Leonard & Øien (2019)** We have mean stock biomass estimate with 95% confidence interval for 2014:2018 for killer-, sperm whale, harbour porpoise and white sided dolphin. We use the 95% CI as the upper limit. **Skern-Mauritzen et al., 2022** We have a mean stock estimate with 95% confidence interval. We use that as the upper limit. Each species within the other baleen whales has their own 95% confidence interval. Those were summed (except killer-, sperm whale, harbour porpoise and white sided dolphin) to achieve the total.

| 39. | CTW14_18Low | The mean biomass of toothed whales for 2014:2018 is at least the lower bound of the estimated mean biomass in 2014:2018 (stock). | 2014:2018 | We assume the biomass of fin- and humpback whale drives the overall dynamics of the other baleen whales and the mean stock biomass with 95% confidence interval (**Leonard & Øien., 2019**) is used as a lower bound with the addition of the other species mean over time lower limit (confidence interval of 95%)(**Skern-Mauritzen et al., 2022**). | **Leonard & Øien (2019)**

We have mean stock biomass estimate with 95% confidence interval for 2014:2018 for killer-, sperm whale, harbour porpoise and white sided dolphin. We use the 95% CI as the lower limit.

Skern-Mauritzen et al., 2022

We have a mean stock estimate with 95% confidence interval. We use that as the lower limit.

Each species within the other baleen whales has their own 95% confidence interval. Those were summed (except killer-, sperm whale, harbour porpoise and white sided dolphin) to achieve the total. |

8.4.2.3 Other baleen whales

| 40. | cOtherBaleenHigh | The biomass of other baleen whales is at most the upper bound of the estimated biomass (stock). | 1988:2021 | We assume that the biomass of toothed whales cannot exceed the upper bound (confidence interval of 95%) of the mean stock upper limit. | **Skern-Mauritzen et al., 2022**

We have a mean stock estimate with 95% confidence interval. We calculate the 99% CI. We use that as the upper limit for the years where our data is lacking. |

					Each species within the other baleen whales has their own 99% confidence interval. Those were summed to achieve the total.
41.	cOtherBaleenLow	The biomass of other baleen whales is at least the lower bound of the estimated biomass (stock).	1988:2021	We assume that the biomass of the toothed whales cannot exceed the upper bound (confidence interval of 95%) of the mean stock lower limit.	**Skern-Mauritzen et al., 2022** We have a mean stock estimate with 95% confidence interval. We calculate the 99% CI. We use that as the lower limit for the years where our data is lacking. Each species within the other baleen whales has their own 99% confidence interval. Those were summed to achieve the total.
42.	COBW02_07High	The mean biomass of other baleen whales for 2002:2007 is at most the upper bound of the estimated mean biomass in 2002:2007 (stock).	2002:2007	We assume the biomass of fin- and humpback whale drives the overall dynamics of the other baleen whales and the mean stock biomass with 95% confidence interval (**Leonard & Øien., 2019**) is used as a lower bound with the addition of the other species mean over time upper limit (confidence interval of 95%)(**Skern-Mauritzen et al., 2022).**	**Leonard & Øien (2019)** We have mean stock biomass estimate with 95% confidence interval for 2002:2007 for fin- and humpback whale. We use the 95% CI as the upper limit. **Skern-Mauritzen et al., 2022** We have a mean stock estimate with 95% confidence interval. We use that as the upper limit. Each species within the other baleen whales has their own 95% confidence interval. Those

					were summed (except fin- and humpback whale) to achieve the total.
43.	COBW02_07Low	The mean biomass of other baleen whales for 2002:2007 is at least the lower bound of the estimated mean biomass in 2002:2007 (stock).	2002:2007	We assume the biomass of fin- and humpback whale drives the overall dynamics of the other baleen whales and the mean stock biomass with 95% confidence interval (**Leonard & Øien., 2019**) is used as a lower bound with the addition of the other species mean over time lower limit (confidence interval of 95%)(**Skern-Mauritzen et al., 2022**).	**Leonard & Øien (2019)** We have mean stock biomass estimate with 95% confidence interval for 2002:2007 for fin- and humpback whale. We use the 95% CI as the lower limit. **Skern-Mauritzen et al., 2022** We have a mean stock estimate with 95% confidence interval. We use that as the lower limit. Each species within the other baleen whales has their own 95% confidence interval. Those were summed (except fin- and humpback whale) to achieve the total.
44.	COBW08_13High	The mean biomass of other baleen whales for 2008:2013 is at most the upper bound of the estimated mean biomass in 2008:2013 (stock).	2008:2013	We assume the biomass of fin- and humpback whale drives the overall dynamics of the other baleen whales and the mean stock biomass with 95% confidence interval (**Leonard & Øien., 2019**) is used as a upper bound with the addition of the other species mean over time lower limit (confidence interval of 95%)(**Skern-Mauritzen et al., 2022**).	**Leonard & Øien (2019)** We have mean stock biomass estimate with 95% confidence interval for 2008:2013 for fin- and humpback whale. We use the 95% CI as the upper limit. **Skern-Mauritzen et al., 2022**

					We have a mean stock estimate with 95% confidence interval. We use that as the upper limit. Each species within the other baleen whales has their own 95% confidence interval. Those were summed (except fin- and humpback whale) to achieve the total.
45.	COBW08_13Low	The mean biomass of other baleen whales for 2008:2013 is at least the lower bound of the estimated mean biomass in 2008:2013 (stock).	2008:2013	We assume the biomass of fin- and humpback whale drives the overall dynamics of the other baleen whales and the mean stock biomass with 95% confidence interval (**Leonard & Øien., 2019**) is used as a lower bound with the addition of the other species mean over time lower limit (confidence interval of 95%)(**Skern-Mauritzen et al., 2022**).	**Leonard & Øien (2019)** We have mean stock biomass estimate with 95% confidence interval for 2008:2013 for fin- and humpback whale. We use the 95% CI as the lower limit. **Skern-Mauritzen et al., 2022** We have a mean stock estimate with 95% confidence interval. We use that as the lower limit. Each species within the other baleen whales has their own 95% confidence interval. Those were summed (except fin- and humpback whale) to achieve the total.
46.	COBW14_18High	The mean biomass of other baleen whales for 2014:2018 is at most the upper bound of the	2014:2018	We assume the biomass of fin- and humpback whale drives the overall dynamics of the other baleen whales and the mean stock biomass with 95%	**Leonard & Øien (2019)** We have mean stock biomass estimate with 95% confidence interval for 2014:2018 for fin-

		estimated mean biomass in 2014:2018 (stock).		confidence interval (**Leonard & Øien., 2019**) is used as a upper bound with the addition of the other species mean over time lower limit (confidence interval of 95%)(**Skern-Mauritzen et al., 2022**).	and humpback whale. We use the 95% CI as the upper limit. **Skern-Mauritzen et al., 2022** We have a mean stock estimate with 95% confidence interval. We use that as the upper limit. Each species within the other baleen whales has their own 95% confidence interval. Those were summed (except fin- and humpback whale) to achieve the total.
47.	COBW14_18Low	The mean biomass of other baleen whales for 2014:2018 is at least the lower bound of the estimated mean biomass in 2014:2018 (stock).	2014:2018	We assume the biomass of fin- and humpback whale drives the overall dynamics of the other baleen whales and the mean stock biomass with 95% confidence interval (**Leonard & Øien., 2019**) is used as a lower bound with the addition of the other species mean over time lower limit (confidence interval of 95%)(**Skern-Mauritzen et al., 2022**).	**Leonard & Øien (2019)** We have mean stock biomass estimate with 95% confidence interval for 2014:2018 for fin- and humpback whale. We use the 95% CI as the lower limit. **Skern-Mauritzen et al., 2022** We have a mean stock estimate with 95% confidence interval. We use that as the lower limit. Each species within the other baleen whales has their own 95% confidence interval. Those

					were summed (except fin- and humpback whale) to achieve the total.

8.4.2.4   Seals

48.	cSealHigh	The biomass of seals is at most the upper bound of harp seal biomass, plus the upper bound of the estimated biomass of the other seals present (stock).	1988:2019	We assume the biomass of harp seal drives the overall dynamics of the seals and the upper bound of the annual stock assessment (**ICES 2019 WGIHARP**) is used with the addition of the other species mean over time upper limit (confidence interval of 95%)(**Skern-Mauritzen et al., 2022**)	**ICES 2019 WGIHARP Figure 2.3 ICES 2019 WGIHARP Figure 2.5** We have annual stock estimates with 95% confidence interval from the Greenland Sea (55% in the Norwegian and Barents Sea) and Barents Sea harp seal. **Skern-Mauritzen et al., 2022** We have a mean stock estimate with 95% confidence interval. We use that as the upper limit. Each species within the seals has their own 95% confidence interval. Those were summed (except harp seal) to achieve the total.
49.	cSealLow	The biomass of seals is at least the lower bound of harp seal biomass, plus the lower bound of the	1988:2019	We assume the biomass of harp seal drives the overall dynamics of the seals and the lower bound of the annual stock assessment (**ICES 2019 WGIHARP**) is used with the addition of the other species mean over time lower limit	**ICES 2019 WGIHARP Figure 2.3 ICES 2019 WGIHARP Figure 2.5** We have annual stock estimates with 95% confidence interval from the Greenland Sea

| | | | | | (confidence interval of 95%)(**Skern-Mauritzen et al., 2022**). | (55% in the Norwegian and Barents Sea) and Barents Sea harp seal.

Skern-Mauritzen et al., 2022

We have a mean stock estimate with 95% confidence interval. We use that as the upper limit.

Each species within the seals has their own 95% confidence interval. Those were summed (except harp seal) to achieve the total. |

estimated biomass of the other seals present (stock).

8.4.3   Fisheries and hunting

Row	Name	Constraints	Time-period	Description	References
50.	CHerringNSFisheries	Flux from herring in the Norwegian Sea to pelagic fisheries is equal to the observed catches.	**1988:2021**	We assume that the catches of herring are equal to the observed catches done by the pelagic fisheries.	**ICES 2022 WGWIDE summarised in STOCK ASSESSMENT GRAPHS** We have the total catch of Norwegian spring spawning herring by fisheries and use that directly as the catch.
51.	CBlueWhitingFisheries	Flux from blue whiting in the Norwegian Sea to pelagic fisheries is equal to the observed catches.	**1988:2021**	We assume that the catches of blue whiting are equal to the observed catches done by the pelagic fisheries.	**ICES 2022 WGWIDE summarised in STOCK ASSESSMENT GRAPHS** We have the total catch of blue whiting by fisheries and use that directly as the catch.

52.	CmackerelFisheries	Flux from mackerel in the Norwegian Sea to pelagic fisheries is equal to the observed catches.	1988:2021	We assume that the catches of mackerel are equal to the observed catches done by the pelagic fisheries.	ICES 2022 WGWIDE summarised in STOCK ASSESSMENT GRAPHS We have the total catch of mackerel by fisheries and use that directly as the catch.
53.	CCodFishery	Flux from cod in the Barents Sea to demersal fisheries is equal to the observed catches.	1988:2021	We assume that the catches of cod are equal to the observed catches done by the demersal fisheries.	ICES 2022 AFWG Table 3.18 We have the total catch of cod by fisheries and use that directly as the catch.
54.	CCapelinFishery	Flux from capelin in the Barents Sea to pelagic fisheries is equal to the observed catches.	1988:2021	We assume that the catches of capelin are equal to the observed catches done by the pelagic fisheries.	ICES 2022 AFWG summarised in STOCK ASSESSMENT GRAPHS We have the total catch of mackerel by fisheries and use that directly as the catch.
55.	COtherDemersalFishery	Flux from other demersal fish in the Barents Sea to demersal fisheries is equal to the observed catches.	1988:2021	We assume that the catches of saithe, haddock, Greenland halibut, and golden redfish are equal to the observed catches done by the demersal fisheries.	Saithe: ICES 2021 AFWG summarised in STOCK ASSESSMENT GRAPHS. We have the total catch of saithe by fisheries and use that directly as the catch. Haddock: ICES 2021 AFWG summarised in STOCK ASSESSMENT GRAPHS We have the total catch of haddock by fisheries and use that directly as the catch. Greenland halibut: ICES 2021 AFWG summarised in STOCK ASSESSMENT GRAPHS

| | | | | | We have the total catch of Greenland halibut by fisheries and use that directly as the catch.

Golden redfish: ICES 2021 AFWG summarised in STOCK ASSESSMENT GRAPHS
We have the total catch of golden redfish by fisheries and use that directly as the catch.

Long rough dab:

No catch registered |
| 56. | CMinkeWhaleFishery | Flux from minke whale to whaling fisheries is equal to the observed catches. | 1988:2021 | We assume that the annual individual catches of minke whale multiplied by the average weight of one minke whale are equal to the observed catches done by the whaling fisheries. | NAMMCO Catch Database

IWC total catches

We have annual catch data that is presented in individuals caught. This was multiplied by the average weight of one minke whale in thousand tonnes. This was used to equal the catch. |

Row	Name	Constraints	Time-period	Description	References
57.	CSealFishery	Flux from seals to whaling fisheries is equal to the observed catches.	1988:2021	We assume that the annual individual catches of seals multiplied by the average weight of the specific seal's weight are equal to the observed catches done by the whaling fisheries.	**ICES 2019 WGHARP Annex 6 & 7** We have annual individual catch data of hooded and harp seals. This were multiplied by the average weight of one hooded/harp seal in thousand tonnes. NAMMCO Catch Database We have annual catch data that is presented in individuals caught. This was multiplied by the average weight of the specific seal in thousand tonnes.

8.4.4 Consumption and diet of fish in the Norwegian Sea

8.4.4.1 Norwegian spring spawning herring

Ro w	Name	Constraints	Time-period	Description	References
58.	CHerringUpper ConsumptionRest	The total consumption of herring divided by its biomass is at most 120%	1988:2004, 2011:2021	We have data on the biomass consumption ratio from 2005 to 2010 for herring. We have taken the average of the ratios for these 6 years and then assume that the maximum possible	**Bachiller et al. (2018)** - Figure 9 - The ratio is consumption/biomass

		of the average observed ratio.		value of the ratio in a year is 120% of the observed average.	- Consumption = Sum of the flux toward herring - Sum of the flux toward herring = biomass * value of the ratio
59.	CHerringLower ConsumptionRest	The total consumption of herring divided by its biomass is at least 3 times less than the average observed ratio.	1988:2004, 2011:2021	We have data on the biomass consumption ratio from 2005 to 2010 for herring. We have taken the average of the ratios for these 6 years and then assume that the minimum possible value of the ratio in any one year is 3 times less than the observed average.	**Bachiller et al. (2018)** - Figure 9 - The ratio is consumption/biomass - Consumption = Sum of the flux toward herring - Sum of the flux toward herring = biomass * value of the ratio
60.	CCBHerringTotal UpperConsumpti on05-10	The total consumption of herring divided by its biomass is at most 120% of the average observed ratio.	2005:2010	We have data on the biomass consumption ratio from 2005 to 2010 for herring. We assume that the maximum possible value of the ratio in a year is 120% of the observed value for a given year.	**Bachiller et al. (2018)** - Figure 9 - The ratio is consumption/biomass - Consumption = Sum of the flux toward herring - Sum of the flux toward herring = biomass * value of the ratio
61.	CCBHerringTotal LowerConsumpti	The total consumption of herring divided by its	2005:2010	We have data on the biomass consumption ratio from 2005 to 2010	**Bachiller et al. (2018)**

	on 05-10	biomass is at least 3 times less than the average observed ratio.		for herring. We assume that the minimum possible value of the ratio is 3 times less than the observed value for a given year.	- Figure 9 - The ratio is consumption/biomass - Consumption = Sum of the flux toward herring - Sum of the flux toward herring = biomass * value of the ratio
62.	CZooPlanktonNS _ HerringNSMean High	The mean upper percentage of zooplankton in the diet of herring in the Norwegian Sea is equal to the reported mean upper percentage.	1988:2021	We assume that the mean upper percentage of zooplankton in the diet of herring in the Norwegian Sea generated by the model made by Planque et al., 2022 is equal to the mean upper percentage of zooplankton in the diet of herring in the Norwegian Sea.	**Planque et al. (2022)** The model output was analysed and used to gather the diet composition of herring in the Norwegian Sea.
63.	CZooPlanktonNS _ HerringNSMeanL ow	The mean lower percentage of zooplankton in the diet of herring in the Norwegian Sea is equal to the reported mean lower percentage.	1988:2021	We assume that the mean lower percentage of zooplankton in the diet of herring in the Norwegian Sea generated by the model made by Planque et al., 2022 is equal to the mean lower percentage of zooplankton in the diet of herring in the Norwegian Sea.	**Planque et al. (2022)** The model output was analysed and used to gather the diet composition of herring in the Norwegian Sea.
64.	CZooPlanktonNS _ HerringNSUpper	The upper percentage of zooplankton in the diet of herring in the Norwegian Sea is equal to the reported mean diet	1988:2021	We assume that the upper limit of zooplankton in the diet of herring in the Norwegian Sea generated by the model made by Planque et al., 2022 is equal to	**Planque et al. (2022)**

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		fraction plus one in the logit space		the upper limit of zooplankton in the diet of herring in the Norwegian Sea.	The model output was analysed and used to gather the diet composition of herring in the Norwegian Sea.
65.	CKrillNS_HerringNS MeanHigh	The mean upper percentage of krill in the diet of herring in the Norwegian Sea is equal to the reported mean upper percentage.	**1988:2021**	We assume that the mean upper percentage of krill in the diet of herring in the Norwegian Sea generated by the model made by Planque et al., 2022 is equal to the mean upper percentage of krill in the diet of herring in the Norwegian Sea.	**Planque et al. (2022)** The model output was analysed and used to gather the diet composition of herring in the Norwegian Sea.
66.	CKrillNS_HerringNS MeanLow	The mean lower percentage of krill in the diet of herring in the Norwegian Sea is equal to the reported mean lower percentage.	**1988:2021**	We assume that the mean lower percentage of krill in the diet of herring in the Norwegian Sea generated by the model made by Planque et al., 2022 is equal to the mean lower percentage of krill in the diet of herring in the Norwegian Sea.	**Planque et al. (2022)** The model output was analysed and used to gather the diet composition of herring in the Norwegian Sea.
67.	CKrillNS_HerringNS Upper	The upper percentage of krill in the diet of herring in the Norwegian Sea is equal to the reported mean diet fraction plus one in the logit space.	**1988:2003, 2008, 2011, 2017:2021**	We assume that the upper limit of krill in the diet of herring in the Norwegian Sea generated by the model made by Planque et al., 2022 is equal to the upper limit of krill in the diet of herring in the Norwegian Sea.	**Planque et al. (2022)** The model output was analysed and used to gather the diet composition of herring in the Norwegian Sea.

68.	CKrillNS_Herrin gNS DietFractionUppe r 04-07,09-10,12-16	The upper percentage of krill in the diet of herring in the Norwegian Sea is equal to the reported mean diet fraction.	**2004:2007, 2009:2010, 2012:2016**	We assume that the upper limit of krill in the diet of herring in the Norwegian Sea for the years: 2004:2007, 2009:2010, 2012:2016 acquired from Planque et al., 2022 is equal to the upper limit of krill in the diet of herring in the Norwegian Sea.	**Planque et al. (2022)** The model input was acquired and used to define the diet composition of herring in the Norwegian Sea for the years 2004:2007, 2009:2010, 2012:2016. This data is mentioned to be unpublished IMR data.
69.	CKrillNS_Herrin gNS DietFractionUppe r 04-07,09-10,12-16	The lower percentage of krill in the diet of herring in the Norwegian Sea is equal to the reported mean diet fraction.	**2004:2007, 2009:2010, 2012:2016**	We assume that the lower limit of krill in the diet of herring in the Norwegian Sea for the years: 2004:2007, 2009:2010, 2012:2016 acquired from Planque et al., 2022 is equal to the lower limit of krill in the diet of herring in the Norwegian Sea.	**Planque et al. (2022)** The model input was acquired and used to define the diet composition of herring in the Norwegian Sea for the years 2004:2007, 2009:2010, 2012:2016. This data is mentioned to be unpublished IMR data.

8.4.4.2 Blue whiting

70.	BlueWhitingUp per ConsumptionRe st	The total consumption of blue whiting divided by its biomass is at most 120% of the average observed ratio.	**1988:2004, 2011:2020**	We have data on the biomass consumption ratio from 2005 to 2010 for blue whiting. We have taken the average of the ratios for these 6 years and then assume that the maximum possible value of the ratio in a year is 120% of the observed average.	**Bachiller et al. (2018)** - Figure 9 - The ratio is consumption/biomass - Consumption = Sum of the flux toward herring

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	*				- Sum of the flux toward herring = biomass * value of the ratio.
71.	CBlueWhitingLowerConsumptionRest	The total consumption of blue whiting divided by its biomass is at least 3 times less than the average observed ratio.	1988:2004, 2011:2020	We have data on the biomass consumption ratio from 2005 to 2010 for blue whiting. We have taken the average of the ratios for these 6 years and then assume that the minimum possible value of the ratio in any one year is 3 times less than the observed average.	**Bachiller et al. (2018)** - Figure 9 - The ratio is consumption/biomass - Consumption = Sum of the flux toward herring - Sum of the flux toward herring = biomass * value of the ratio.
72.	CBlueWhitingUpper Consumption05-10	The total consumption of blue whiting divided by its biomass is at most 120% of the ratio observed for a given year.	2005:2010	We have data on the biomass consumption ratio from 2005 to 2010 for blue whiting. We assume that the maximum possible value of the ratio in a year is 120% of the observed value for a given year.	**Bachiller et al. (2018)** - Figure 9 - The ratio is consumption/biomass - Consumption = Sum of the flux toward herring - Sum of the flux toward herring = biomass * value of the ratio.

73.	CBlueWhitingLowerConsumption05-10	The total consumption of blue whiting divided by its biomass is at least 3 times less than the ratio observed for a given year.	2005:2010	We have data on the biomass consumption ratio from 2005 to 2010 for blue whiting. We assume that the minimum possible value of the ratio is 3 times less than the observed value for a given year.	**Bachiller et al. (2018)** - Figure 9 - The ratio is consumption/biomass - Consumption = Sum of the flux toward herring - Sum of the flux toward herring = biomass * value of the ratio.
74.	COutsideResources_BlueWhitingNSUpper	Flux from outside resources to blue whiting is at most 1.2 times more than blue whiting consumption in the Norwegian sea (sum of all the flux toward blue whiting in the Norwegian sea)	1988:2021	Dommasnes has made an estimation of the consumption ratio of blue whiting in and out the Norwegian sea. We assume that the consumption of blue whiting outside the Norwegian sea is at most 1.2 times more than its consumption in the Norwegian.	**Dommasnes, 2001** - Ratio of consumption in/out the Norwegian sea.
75.	COutsideResources_BlueWhitingNS Lower	Flux from outside resources to blue whiting is at least 1/1.2 (~0.83) times less than blue whiting consumption in the Norwegian sea (sum of all the flux toward blue	1988:2021	Dommasnes has made an estimation of the consumption ratio of blue whiting in and out the Norwegian sea. We assume that the consumption of blue whiting outside the Norwegian sea is at least 1/1.2 (~0.83) less than times its consumption in the Norwegian.	**Dommasnes, 2001** - Ratio of consumption in/out the Norwegian sea.

		whiting in the Norwegian sea)			
76.	CZooPlanktonNS_ BlueWhitingNS MeanHigh	The mean upper percentage of zooplankton in the diet of blue whiting in the Norwegian Sea is equal to the reported mean upper percentage.	1988:2021	We assume that the mean upper percentage of zooplankton in the diet of blue whiting in the Norwegian Sea generated by the model made by Planque et al., 2022 is equal to the mean upper percentage of zooplankton in the diet of blue whiting in the Norwegian Sea.	**Planque et al. (2022)** The model output was analysed and used to gather the diet composition of blue whiting in the Norwegian Sea.
77.	CZooPlanktonNS_ BlueWhitingNS MeanLow	The mean lower percentage of zooplankton in the diet of blue whiting in the Norwegian Sea is equal to the reported mean lower percentage.	1988:2021	We assume that the mean lower percentage of zooplankton in the diet of blue whiting in the Norwegian Sea generated by the model made by Planque et al., 2022 is equal to the mean lower percentage of zooplankton in the diet of blue whiting in the Norwegian Sea.	**Planque et al. (2022)** The model output was analysed and used to gather the diet composition of blue whiting in the Norwegian Sea.
78.	CZooPlanktonNS_ BlueWhitingNS Upper	The upper percentage of zooplankton in the diet of blue whiting in the Norwegian Sea is equal to the reported mean diet fraction plus one in the logit space	1988:2021	We assume that the upper limit of zooplankton in the diet of blue whiting in the Norwegian Sea generated by the model made by Planque et al., 2022 is equal to the upper limit of zooplankton in the diet of blue whiting in the Norwegian Sea.	**Planque et al. (2022)** The model output was analysed and used to gather the diet composition of blue whiting in the Norwegian Sea.

79.	CKrillNS_ BlueWhitingNS MeanHigh	The mean upper percentage of krill in the diet of blue whiting in the Norwegian Sea is equal to the reported mean upper percentage.	1988:2021	We assume that the mean upper percentage of krill in the diet of blue whiting in the Norwegian Sea generated by the model made by Planque et al., 2022 is equal to the mean upper percentage of krill in the diet of blue whiting in the Norwegian Sea.	**Planque et al. (2022)** The model output was analysed and used to gather the diet composition of blue whiting in the Norwegian Sea.
80.	CKrillNS_ BlueWhitingNS MeanLow	The mean lower percentage of krill in the diet of blue whiting in the Norwegian Sea is equal to the reported mean lower percentage.	1988:2021	We assume that the mean lower percentage of krill in the diet of blue whiting in the Norwegian Sea generated by the model made by Planque et al., 2022 is equal to the mean lower percentage of krill in the diet of blue whiting in the Norwegian Sea.	**Planque et al. (2022)** The model output was analysed and used to gather the diet composition of blue whiting in the Norwegian Sea.
81.	CKrillNS_ BlueWhitingNS Upper	The upper percentage of krill in the diet of blue whiting in the Norwegian Sea is equal to the reported mean diet fraction plus one in the logit space	1988:2021	We assume that the upper limit of krill in the diet of blue whiting in the Norwegian Sea generated by the model made by Planque et al., 2022 is equal to the upper limit of krill in the diet of blue whiting in the Norwegian Sea.	**Planque et al. (2022)** The model output was analysed and used to gather the diet composition of blue whiting in the Norwegian Sea.
82.	CKrillNS_ BlueWhitingNS FractionUpper	The upper percentage of krill in the diet of blue whiting in the Norwegian Sea is equal to the	2004:2007, 2009:2010, 2012:2016	We assume that the upper limit of krill in the diet of blue whiting in the Norwegian Sea for the years: 2004:2007, 2009:2010, 2012:2016	**Planque et al. (2022)** The model input was acquired and used to define the diet composition of blue whiting in the Norwegian Sea for the years 2004:2007,

	04-07,09-10,12-16	reported mean diet fraction.		acquired from Planque et al., 2022 is equal to the upper limit of krill in the diet of blue whiting in the Norwegian Sea.	2009:2010, 2012:2016. This data is mentioned to be unpublished IMR data.
83.	CKrillNS_BlueWhitingNS FractionLower 04-07,09-10,12-16	The lower percentage of krill in the diet of blue whiting in the Norwegian Sea is equal to the reported mean diet fraction.	2004:2007, 2009:2010, 2012:2016	We assume that the lower limit of krill in the diet of blue whiting in the Norwegian Sea for the years: 2004:2007, 2009:2010, 2012:2016 acquired from Planque et al., 2022 is equal to the lower limit of krill in the diet of blue whiting in the Norwegian Sea.	**Planque et al. (2022)** The model input was acquired and used to define the diet composition of blue whiting in the Norwegian Sea for the years 2004:2007, 2009:2010, 2012:2016. This data is mentioned to be unpublished IMR data.
84.	CMesopelagicAnd OtherNS_ BlueWhitingNS MeanHigh	The mean upper percentage of mesopelagic organisms and other fish in the diet of blue whiting in the Norwegian Sea is equal to the reported mean upper percentage.	1988:2021	We assume that the mean upper percentage of mesopelagic organisms and other fish in the diet of blue whiting in the Norwegian Sea generated by the model made by Planque et al., 2022 is equal to the mean upper percentage of mesopelagic organisms and other fish in the diet of blue whiting in the Norwegian Sea.	**Planque et al. (2022)** The model output was analysed and used to gather the diet composition of blue whiting in the Norwegian Sea.
85.	CMesopelagicAnd OtherNS_ BlueWhitingNS	The mean lower percentage of mesopelagic organisms and other fish in the diet of blue whiting in the Norwegian Sea is equal to	1988:2021	We assume that the mean lower percentage of mesopelagic organisms and other fish in the diet of blue whiting in the Norwegian Sea generated by the model made by Planque et al., 2022 is equal to the mean lower percentage of	**Planque et al. (2022)** The model output was analysed and used to gather the diet composition of blue whiting in the Norwegian Sea.

	MeanLow	the reported mean lower percentage.		krill in the diet of blue whiting in the Norwegian Sea.	
86.	CMesopelagicA nd OtherNS_ BlueWhitingNS Upper	The upper percentage of mesopelagic organisms and other fish in the diet of blue whiting in the Norwegian Sea is equal to the reported mean diet fraction plus one in the logit space	**1988:2021**	We assume that the upper limit of mesopelagic organisms and other fish in the diet of blue whiting in the Norwegian Sea generated by the model made by Planque et al., 2022 is equal to the upper limit of krill in the diet of blue whiting in the Norwegian Sea.	**Planque et al. (2022)** The model output was analysed and used to gather the diet composition of blue whiting in the Norwegian Sea.

8.4.4.3 Atlantic mackerel

87.	CMackerelUpper ConsumptionRest	The total consumption of mackerel divided by its biomass is at most 120% of the average observed ratio.	**1988:2004, 2011:2021**	We have data on the biomass consumption ratio from 2005 to 2010 for mackerel. We have taken the average of the ratios for these 6 years and then assume that the maximum possible value of the ratio in a year is 120% of the observed average.	**Bachiller et al. (2018)** **-** Figure 9 - The ratio is consumption/biomass - Consumption = Sum of the flux toward herring - Sum of the flux toward herring = biomass * value of the ratio

88.	CMackerelLowerConsumptionRest	The total consumption of mackerel divided by its biomass is at least 3 times less than the average observed ratio.	1988:2004, 2011:2021	We have data on the biomass consumption ratio from 2005 to 2010 for mackerel. We have taken the average of the ratios for these 6 years and then assume that the minimum possible value of the ratio in any one year is 3 times less than the observed average.	Bachiller et al. (2018) - Figure 9 - The ratio is consumption/biomass - Consumption = Sum of the flux toward herring - Sum of the flux toward herring = biomass * value of the ratio
89.	CCBMackerelTotal UpperConsumption 05-10	The total consumption of mackerel divided by its biomass is at most 120% of the ratio observed for a given year	2005:2010	We have data on the biomass consumption ratio from 2005 to 2010 for mackerel. We assume that the maximum possible value of the ratio in a year is 120% of the observed value for a given year.	Bachiller et al. (2018) - Figure 9 - The ratio is consumption/biomass - Consumption = Sum of the flux toward herring - Sum of the flux toward herring = biomass * value of the ratio
90.	CCBMackerelTotal LowerConsumption 05-10	The total consumption of mackerel divided by its biomass is at least 3 times less than the ratio observed for a given year	2005:2010	We have data on the biomass consumption ratio from 2005 to 2010 for mackerel. We assume that the minimum possible value of the ratio is 3 times less than the observed value for a given year.	Bachiller et al. (2018) - Figure 9 - The ratio is consumption/biomass

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					- Consumption = Sum of the flux toward herring - Sum of the flux toward herring = biomass * value of the ratio
91.	CoutsideResources_MackerelNS Upper	Flux from outside resources to mackerel is at most 7 times more than mackerel consumption in the Norwegian sea (sum of all the flux toward mackerel in the Norwegian sea)	**1988:2006, 2008:2009, 2015:2021**	For mackerel, Dommasnes et al. (2001) assumed that 25% of the stocks feeds in the Norwegian Sea during the summer season (50% of the year), and consequently used 0.50*0.25 = 12.5% as the proportion of the stock biomass present in the Norwegian Sea. We assume that the consumption of mackerel outside the Norwegian sea is at most 7 times more than its consumption in the Norwegian.	**Dommasnes, 2001** - Ratio of consumption in/out the Norwegian sea
92.	CoutsideResources_MackerelNS Lower	Flux from outside resources to mackerel is at least equal to mackerel consumption in the Norwegian sea (sum of all the flux toward mackerel in the Norwegian sea)	**1988:2006, 2008:2009, 2015:2021**	For mackerel, Dommasnes et al. (2001) assumed that 25% of the stocks feeds in the Norwegian Sea during the summer season (50% of the year), and consequently used 0.50*0.25 = 12.5% as the proportion of the stock biomass present in the Norwegian Sea. We assume that the consumption of mackerel outside the Norwegian sea is at least equal to its consumption in the Norwegian.	**Dommasnes, 2001** - Ratio of consumption in/out the Norwegian sea

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93.	COutsideResources_MackerelUpper 07,10-14	Flux from outside resources to mackerel is at most the ratio of the proportions of mackerel observed in and out of the Norwegian sea	2007, 2010:2014	We have data on the proportion of mackerel stock in the Norwegian sea. We have used the half of the proportions reported by Nøttestad et al. 2016 as an upper bound.	**Nøttestad et al., 2016** - Ratio of mackerel consumption in/out the Norwegian sea
94.	COutsideResources_MackerelLower 07,10-14	Flux from outside resources to mackerel is at least the ratio of the proportion of mackerel observed in and out of the Norwegian sea	2007, 2010:2014	We have data on the proportion of mackerel stock in the Norwegian sea. We have used the half of the proportions reported by Nøttestad et al. 2016 as a lower bound.	**Nøttestad et al., 2016** - Ratio of mackerel consumption in/out the Norwegian sea
95.	CZooPlanktonNS_ MackerelNS MeanHigh	The mean upper percentage of zooplankton in the diet of mackerel in the Norwegian Sea is equal to the reported mean upper percentage.	1988:2021	We assume that the mean upper percentage of zooplankton in the diet of mackerel in the Norwegian Sea generated by the model made by Planque et al., 2022 is equal to the mean upper percentage of zooplankton in the diet of mackerel in the Norwegian Sea.	**Planque et al., 2022** The model output was analysed and used to gather the diet composition of mackerel in the Norwegian Sea.
96.	CZooPlanktonNS_ MackerelNS MeanLow	The mean lower percentage of zooplankton in the diet of mackerel in the Norwegian Sea is equal to the reported mean lower percentage.	1988:2021	We assume that the mean lower percentage of zooplankton in the diet of mackerel in the Norwegian Sea generated by the model made by Planque et al., 2022 is equal to the mean lower percentage of zooplankton	**Planque et al., 2022** The model output was analysed and used to gather the diet composition of mackerel in the Norwegian Sea.

				in the diet of mackerel in the Norwegian Sea.	
97.	CZooPlanktonNS_ MackerelNS Upper	The upper percentage of zooplankton in the diet of mackerel in the Norwegian Sea is equal to the reported mean diet fraction plus one in the logit space	**1988:2021**	We assume that the upper limit of zooplankton in the diet of mackerel in the Norwegian Sea generated by the model made by Planque et al., 2022 is equal to the upper limit of zooplankton in the diet of mackerel in the Norwegian Sea.	**Planque et al., 2022** The model output was analysed and used to gather the diet composition of mackerel in the Norwegian Sea.
98.	CKrillNS_ MackerelNS MeanHigh	The mean upper percentage of krill in the diet of mackerel in the Norwegian Sea is equal to the reported mean upper percentage.	**1988:2021**	We assume that the mean upper percentage of krill in the diet of mackerel in the Norwegian Sea generated by the model made by Planque et al., 2022 is equal to the mean upper percentage of krill in the diet of mackerel in the Norwegian Sea.	**Planque et al., 2022** The model output was analysed and used to gather the diet composition of mackerel in the Norwegian Sea.
99.	CKrillNS_ MackerelNS MeanLow	The mean lower percentage of krill in the diet of mackerel in the Norwegian Sea is equal to the reported mean lower percentage.	**1988:2021**	We assume that the mean lower percentage of krill in the diet of mackerel in the Norwegian Sea generated by the model made by Planque et al., 2022 is equal to the mean lower percentage of krill in the diet of mackerel in the Norwegian Sea.	**Planque et al., 2022** The model output was analysed and used to gather the diet composition of mackerel in the Norwegian Sea.
100	CKrillNS_ MackerelNS	The upper percentage of krill in the diet of mackerel in the	**1988:2021**	We assume that the upper limit of krill in the diet of mackerel in the Norwegian Sea generated by the model	**Planque et al., 2022**

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	Upper	Norwegian Sea is equal to the reported mean diet fraction plus one in the logit space		made by Planque et al., 2022 is equal to the upper limit of krill in the diet of mackerel in the Norwegian Sea.	The model output was analysed and used to gather the diet composition of mackerel in the Norwegian Sea.
101	CKrillNS_ MackerelNSDiet FractionUpper 04-07,09-10,12-16	The upper percentage of krill in the diet of mackerel in the Norwegian Sea is equal to the reported mean diet fraction.	2004:2007, 2009:2010, 2012:2016	We assume that the upper limit of krill in the diet of mackerel in the Norwegian Sea for the years: 2004:2007, 2009:2010, 2012:2016 acquired from Planque et al., 2022 is equal to the upper limit of krill in the diet of mackerel in the Norwegian Sea.	**Planque et al., 2022** The model input was acquired and used to define the diet composition of mackerel in the Norwegian Sea for the years 2004:2007, 2009:2010, 2012:2016. This data is mentioned to be unpublished IMR data.
102	CKrillNS_ MackerelNSDiet FractionLower 04-07,09-10,12-16	The lower percentage of krill in the diet of mackerel in the Norwegian Sea is equal to the reported mean diet fraction.	2004:2007, 2009:2010, 2012:2016	We assume that the lower limit of krill in the diet of mackerel in the Norwegian Sea for the years: 2004:2007, 2009:2010, 2012:2016 acquired from Planque et al., 2022 is equal to the lower limit of krill in the diet of mackerel in the Norwegian Sea.	**Planque et al., 2022** The model input was acquired and used to define the diet composition of mackerel in the Norwegian Sea for the years 2004:2007, 2009:2010, 2012:2016. This data is mentioned to be unpublished IMR data.

8.4.5 Consumption and diet of fish in the Barents Sea

8.4.5.1 Atlantic cod

Row	Name	Constraints	Time-period	Description	References
103	CCodTotal Consumption	The upper limit of consumption by cod is equal to the reported annual total consumption by cod times 120%.	1988:2021	We assume that the annual total consumption by cod times 1.2 (120%) equals the upper limit of consumption each year by cod.	**Personal communitaction with Bjarte Bogstad** We have annual total consumption by cod. Which can be used to define an upper limit of total consumption by cod.
104	CAmphipods_Cod TotalConsumption	The upper limit of consumption of amphipods by cod is equal to the reported annual total consumption of amphipods by cod times 120%.	1988:2021	We assume that the annual total consumption of amphipods by cod times 1.2 (120%) equals the upper limit of consumption of amphipods each year by cod.	**Personal communitaction with Bjarte Bogstad** We have annual total consumption by cod. Which can be used to define an upper limit of total consumption by cod.
105	CKrillBS_Cod TotalConsumption	The upper limit of consumption of krill in the Barents Sea by cod is equal to the reported annual total consumption of krill in the Barents Sea by cod times 120%.	1988:2021	We assume that the annual total consumption of krill in the Barents Sea by cod times 1.2 (120%) equals the upper limit of consumption of krill in the Barents Sea each year by cod.	**Personal communitaction with Bjarte Bogstad** We have annual total consumption by cod. Which can be used to define an upper limit of total consumption by cod.

106	CCapelin_Cod TotalConsumpti on	The upper limit of consumption of capelin by cod is equal to the reported annual total consumption of capelin by cod times 120%.	1988:2021	We assume that the annual total consumption of capelin by cod times 1.2 (120%) equals the upper limit of consumption of capelin each year by cod.	**Personal communitaction with Bjarte Bogstad** We have annual total consumption by cod. Which can be used to define an upper limit of total consumption by cod.
107	CCod_Cod TotalConsumpti on	The upper limit of consumption of cod by cod is equal to the reported annual total consumption of cod by cod times 120%.	1988:2021	We assume that the annual total consumption of cod by cod times 1.2 (120%) equals the upper limit of consumption of cod each year by cod.	**Personal communitaction with Bjarte Bogstad** We have annual total consumption by cod. Which can be used to define an upper limit of total consumption by cod.
108	COD_Cod TotalConsumpti on	The upper limit of consumption of other demersal fish by cod is equal to the reported annual total consumption of other demersal fish by cod times 120%.	1988:2021	We assume that the annual total consumption of other demersal fish by cod times 1.2 (120%) equals the upper limit of consumption of other demersal fish each year by cod.	**Personal communitaction with Bjarte Bogstad** We have annual total consumption by cod. Which can be used to define an upper limit of total consumption by cod.
109	CBenthos_Cod TotalConsumpti on	The upper limit of consumption of benthic organisms by cod is equal to the reported annual total consumption of benthic organisms by cod times 120%.	1988:2021	We assume that the annual total consumption of benthic organisms by cod times 1.2 (120%) equals the upper limit of consumption of benthic organisms each year by cod.	**Personal communitaction with Bjarte Bogstad** We have annual total consumption by cod. Which can be used to define an upper limit of total consumption by cod.

110	CPolarCod_Cod TotalConsumpti on	The upper limit of consumption of polar cod by cod is equal to the reported annual total consumption of polar cod by cod times 120%.	**1988:2021**	We assume that the annual total consumption of polar cod by cod times 1.2 (120%) equals the upper limit of consumption of polar cod each year by cod.	**Personal communitaction with Bjarte Bogstad** We have annual total consumption by cod. Which can be used to define an upper limit of total consumption by cod.
111	CHerringBS_Co d TotalConsumpti on	The upper limit of consumption of herring in the Barents Sea by cod is equal to the reported annual total consumption of Herring in the Barents Sea by cod times 120%.	**1988:2021**	We assume that the annual total consumption of herring in the Barents Sea by cod times 1.2 (120%) equals the upper limit of consumption of herring in the Barents Sea each year by cod.	**Personal communitaction with Bjarte Bogstad** We have annual total consumption by cod. Which can be used to define an upper limit of total consumption by cod.
112	CCodBS_CodB S FractionMeanU pper	The mean upper percentage of cod in the diet of cod is equal to the reported mean diet fraction plus 0.25 in the logit space.	**1988:2021**	We assume that the mean diet fraction of cod in the diet of cod is equal to the mean diet of cod in cod over the entire time-period.	**Personal communication with Bjarte Bogstad** We have mean diet fraction of cod. These are added and converted to percentages and use as mean over time.
113	CCapelinBS_Co dBS FractionMeanU pper	The mean upper percentage of capelin in the diet of cod is equal to the reported mean diet fraction plus 0.25 in the logit space.	**1988:2021**	We assume that the mean diet fraction of capelin in the diet of cod is equal to the mean diet of capelin in cod over the entire time-period.	**Personal communication with Bjarte Bogstad** We have mean diet fraction of cod. These are added and converted to percentages and use as mean over time.

114	COtherDemersalBS_CodBS FractionMeanUpper	The mean upper percentage of other demersal fish in the diet of cod is equal to the reported mean diet fraction plus 0.25 in the logit space.	1988:2021	We assume that the mean diet fraction of other demersal fish in the diet of cod is equal to the mean diet of other demersal fish in cod over the entire time-period.	**Personal communication with Bjarte Bogstad** We have mean diet fraction of cod. These are added and converted to percentages and use as mean over time.
115	CHerringBS_CodBS FractionMeanUpper	The mean upper percentage of herring in the diet of cod is equal to the reported mean diet fraction plus 0.25 in the logit space.	1988:2021	We assume that the mean diet fraction of herring in the diet of cod is equal to the mean diet of herring in cod over the entire time-period.	**Personal communication with Bjarte Bogstad** We have mean diet fraction of cod. These are added and converted to percentages and use as mean over time.
116	CPolarCodBS_CodBS FractionMeanUpper	The mean upper percentage of polar cod in the diet of cod is equal to the reported mean diet fraction plus 0.25 in the logit space.	1988:2021	We assume that the upper mean diet fraction of polar cod in the diet of cod is equal to the upper mean diet of polar cod in cod over the entire time-period.	**Personal communication with Bjarte Bogstad** We have mean diet fraction of cod. These are added and converted to percentages and use as mean over time.
117	CBenthosBS_CodBSFractionMeanUpper	The mean upper percentage of benthic organisms in the diet of cod is equal to the reported mean diet fraction plus 0.25 in the logit space.	1988:2021	We assume that the upper mean diet fraction of benthic organisms in the diet of cod is equal to the upper mean diet of benthic organisms in cod over the entire time-period.	**Personal communication with Bjarte Bogstad** We have mean diet fraction of cod. These are added and converted to percentages and use as mean over time.

118	CAmphipodsBS_CodBS FractionMeanUpper	The mean upper percentage of amphipods in the diet of cod is equal to the reported mean diet fraction plus 0.25 in the logit space.	**1988:2021**	We assume that the upper mean diet fraction of amphipods in the diet of cod is equal to the upper mean diet of amphipods in cod over the entire time-period.	**Personal communication with Bjarte Bogstad** We have mean diet fraction of cod. These are added and converted to percentages and use as mean over time.
119	CKrillBS_CodBS FractionMeanUpper	The mean upper percentage of krill in the diet of cod is equal to the reported mean diet fraction plus 0.25 in the logit space.	**1988:2021**	We assume that the upper mean diet fraction of krill in the diet of cod is equal to the upper mean diet of krill in cod over the entire time-period.	**Personal communication with Bjarte Bogstad** We have mean diet fraction of cod. These are added and converted to percentages and use as mean over time.
120	CCodBS_CodBS FractionMeanLower	The mean lower percentage of cod in the diet of cod is equal to the reported mean diet fraction minus 0.25 in the logit space.	**1988:2021**	We assume that the lower mean diet fraction of cod in the diet of cod is equal to the lower mean diet of cod in cod over the entire time-period.	**Personal communication with Bjarte Bogstad** We have mean diet fraction of cod. These are added and converted to percentages and use as mean over time.
121	CCapelinBS_CodBS FractionMeanLower	The mean lower percentage of capelin in the diet of cod is equal to the reported mean diet fraction minus 0.25 in the logit space.	**1988:2021**	We assume that the lower mean diet fraction of capelin in the diet of cod is equal to the lower mean diet of capelin in cod over the entire time-period.	**Personal communication with Bjarte Bogstad** We have mean diet fraction of cod. These are added and converted to percentages and use as mean over time.

122	COtherDemersa lBS_CodBS FractionMeanLo wer	The mean lower percentage of other demersal fish in the diet of cod is equal to the reported mean diet fraction minus 0.25 in the logit space.	**1988:2021**	We assume that the lower mean diet fraction of other demersal fish in the diet of cod is equal to the lower mean diet of other demersal fish in cod over the entire time-period.	**Personal communication with Bjarte Bogstad** We have mean diet fraction of cod. These are added and converted to percentages and use as mean over time.
123	CHerringBS_Co dBS FractionMeanLo wer	The mean lower percentage of herring in the diet of cod is equal to the reported mean diet fraction minus 0.25 in the logit space.	**1988:2021**	We assume that the lower mean diet fraction of herring in the diet of cod is equal to the lower mean diet of herring in cod over the entire time-period.	**Personal communication with Bjarte Bogstad** We have mean diet fraction of cod. These are added and converted to percentages and use as mean over time.
124	CPolarCodBS_ CodBS FractionMeanLo wer	The mean lower percentage of polar cod in the diet of cod is equal to the reported mean diet fraction minus 0.25 in the logit space.	**1988:2021**	We assume that the lower mean diet fraction of polar cod in the diet of cod is equal to the lower mean diet of polar cod in cod over the entire time-period.	**Personal communication with Bjarte Bogstad** We have mean diet fraction of cod. These are added and converted to percentages and use as mean over time.
125	CBenthosBS_C odBSFractionM eanLower	The mean lower percentage of benthic organisms in the diet of cod is equal to the reported mean diet fraction minus 0.25 in the logit space.	**1988:2021**	We assume that the lower mean diet fraction of benthic organisms in the diet of cod is at least the lower mean diet of benthic organisms in cod over the entire time-period minus 0.25 in the logit space.	**Personal communication with Bjarte Bogstad** We have mean diet fraction of cod. These are added and converted to percentages and use as mean over time.

126	CAmphipodsBS_CodBS FractionMeanLower	The mean lower percentage of amphipods in the diet of cod is equal to the reported mean diet fraction minus 0.25 in the logit space.	**1988:2021**	We assume that the lower mean diet fraction of amphipods in the diet of cod is equal to the lower mean diet of amphipods in cod over the entire time-period.	**Personal communication with Bjarte Bogstad** We have mean diet fraction of cod. These are added and converted to percentages and use as mean over time.
127	CKrillBS_CodBS FractionMeanLower	The mean lower percentage of krill in the diet of cod is equal to the reported mean diet fraction minus 0.25 in the logit space.	**1988:2021**	We assume that the lower mean diet fraction of krill in the diet of cod is equal to the lower mean diet of krill in cod over the entire time-period.	**Personal communication with Bjarte Bogstad** We have mean diet fraction of cod. These are added and converted to percentages and use as mean over time.

8.4.5.2 Polar cod

128	CCopepodBS_PolarCod FractionUpper	The upper percentage of copepods in the diet of polar cod is equal to the reported mean diet fraction plus one in the logit space	**1988:2021**	We assume that the mean diet fraction of copepods in polar cod plus one in the logit space equals the upper limit of the percentage of copepods in the diet of polar cod.	**Eriksen et al., 2020** We have mean diet fraction of polar cod. These are added and converted to percentages and use as upper limit.
129	CKrillBS_PolarCod	The upper percentage of krill in the diet of polar cod is equal to the reported mean diet	**1988:2021**	We assume that the mean diet fraction of krill in polar cod plus one in the logit space equals the upper limit of the	**Eriksen et al., 2020**

	FractionUpper	fraction plus one in the logit space		percentage of krill in the diet of polar cod.	We have mean diet fraction of polar cod. These are added and converted to percentages and use as upper limit.
130	CAmphipodsBS_PolarCodFractionUpper	The upper percentage of amphipods in the diet of polar cod is equal to the reported mean diet fraction plus one in the logit space	1988:2021	We assume that the mean diet fraction of amphipods in polar cod plus one in the logit space equals the upper limit of the percentage of amphipods in the diet of polar cod.	**Eriksen et al., 2020** We have mean diet fraction of polar cod. These are added and converted to percentages and use as upper limit.
131	CBenthosBS_PolarCodFractionUpper	The upper percentage of amphipods in the diet of polar cod is equal to the reported mean diet fraction plus one in the logit space	1988:2021	We assume that the mean diet fraction of benthic organisms in polar cod plus one in the logit space equals the upper limit of the percentage of benthic organisms in the diet of polar cod.	**Eriksen et al., 2020** We have mean diet fraction of polar cod. These are added and converted to percentages and use as upper limit.
132	CCopepodBS_PolarCodMean	The mean percentage of copepods in the diet of polar cod is equal to the reported mean diet fraction.	1988:2021	We assume that the mean diet fraction of copepods in polar equals mean the percentage of copepods in the diet of polar cod.	**Eriksen et al., 2020** We have mean diet fraction of polar cod. These were modified to conform to our trophospecies.

133	CKrillBS_ PolarCodMean	The mean percentage of krill in the diet of polar cod is equal to the reported mean diet fraction.	1988:2021	We assume that the mean diet fraction of krill in polar cod equals the mean percentage of krill in the diet of polar cod.	**Eriksen et al., 2020** We have mean diet fraction of polar cod. These were modified to conform to our trophospecies.
134	CAmphipodsBS – PolarCodMean	The mean percentage of amphipods in the diet of polar cod is equal to the reported mean diet fraction.	1988:2021	We assume that the mean diet fraction of amphipods in polar equals mean percentage of amphipods in the diet of polar cod.	**Eriksen et al., 2020** We have mean diet fraction of polar cod. These were modified to conform to our trophospecies.
135	CBenthosBS_ PolarCodMean	The mean percentage of benthic organisms in the diet of polar cod is equal to the reported mean diet fraction.	1988:2021	We assume that the mean diet fraction of benthic organisms in polar equals mean percentage of benthic organisms in the diet of polar cod.	**Eriksen et al., 2020** We have mean diet fraction of polar cod. These were modified to conform to our trophospecies.

8.4.5.3   Capelin

136	CKrillBS_Capel inBSFractionUp per	The upper percentage of krill in the diet of capelin is equal to the reported	1988:2021	We assume that the mean diet fraction of krill in capelin plus one in the logit space equals the upper limit of the percentage of krill in the diet of capelin.	**Pedersen et al., 2021**

		mean diet fraction plus one in the logit space			We have mean diet fraction of capelin. These are added and converted to percentages and use as upper limit.
137	CCopepodBS_ CapelinBS FractionUpper	The upper percentage of copepods in the diet of capelin is equal to the reported mean diet fraction plus one in the logit space	**1988:2021**	We assume that the mean diet fraction of copepods in capelin plus one in the logit space equals the upper limit of the percentage of copepods in the diet of capelin.	**Pedersen et al., 2021** We have mean diet fraction of capelin. These are added and converted to percentages and use as upper limit.
138	CKrillBS_Capel inBSFractionMe anUpper	The mean upper percentage of krill in the diet of capelin is equal to the reported mean diet fraction plus 0.25 in the logit space	**1988:2021**	We assume that the mean diet fraction of krill in capelin minus one in the logit space equals the mean upper percentage of krill in the diet of capelin.	**Pedersen et al., 2021** We have mean diet fraction of capelin. These are added and converted to percentages and use as mean.
139	CCopepodBS_ CapelinBS FractionMeanU pper	The mean lower percentage of copepods in the diet of capelin is equal to the reported mean diet fraction plus 0.25 in the logit space	**1988:2021**	We assume that the mean diet fraction of copepods in capelin minus one in the logit space equals the mean upper percentage of copepods in the diet of capelin.	**Pedersen et al., 2021** We have mean diet fraction of capelin. These are added and converted to percentages and use as mean.

140	CKrillBS_Capel inBSFractionMe anLower	The mean lower percentage of krill in the diet of capelin over the entire time-period is equal to the reported mean annual diet minus 0.25 in the logit space.	**1988:2021**	We assume that the mean diet fraction of krill in capelin minus 0.25 in the logit space equals the mean lower percentage of krill in the diet of capelin.	**Pedersen et al., 2021** We have mean diet fraction of capelin. These are added and converted to percentages and use as mean.
141	CCopepodBS_ CapelinBS FractionMeanLo wer	The mean lower percentage of copepods in the diet of capelin over the entire time-period is equal to the reported mean annual diet minus 0.25 in the logit space.	**1988:2021**	We assume that the mean diet fraction of copepods in capelin minus 0.25 in the logit space equals the mean lower percentage of copepods in the diet of capelin.	**Pedersen et al., 2021** We have mean diet fraction of capelin. These are added and converted to percentages and use as mean.

8.4.5.4 Juvenile herring

142	CKrillBS_ HerringBS FractionUpper	The upper percentage of krill in the diet of herring in the Barents Sea is equal to the reported mean diet fraction plus one in the logit space	**1988:2021**	We assume that the mean diet fraction of krill in herring plus one in the logit space equals the upper limit of the percentage of krill in the diet of herring.	**Pedersen et al., 2021** We have mean diet fraction of capelin. These are added and converted to percentages and use as upper limit.
143	CAmphipodsBS _	The upper percentage of amphipods in the diet of herring in the Barents Sea	**1988:2021**	We assume that the mean diet fraction of amphipods in capelin plus one in the logit space equals the upper limit of the	**Pedersen et al., 2021**

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	HerringBS FractionUpper	is equal to the reported mean diet fraction plus one in the logit space		percentage of amphipods in the diet of capelin.	We have mean diet fraction of capelin. These are added and converted to percentages and use as upper limit.
144	CCopepodBS_ HerringBS FractionUpper	The upper percentage of copepods in the diet of herring in the Barents Sea is equal to the reported mean diet fraction plus one in the logit space	**1988:2021**	We assume that the mean diet fraction of copepods in capelin plus one in the logit space equals the upper limit of the percentage of copepods in the diet of capelin.	**Pedersen et al., 2021** We have mean diet fraction of capelin. These are added and converted to percentages and use as upper limit.
145	CKrillBS_ HerringBS Mean	The mean percentage of krill in the diet of herring in the Barents Sea is equal to the reported mean diet fraction.	**1988:2021**	We assume that the mean diet fraction of krill in herring equals the mean percentage of krill in the diet of herring.	**Pedersen et al., 2021** We have mean diet fraction of capelin. These are added and converted to percentages and use as lower limit.
146	CAmphipodsBS – HerringBS Mean	The mean percentage of amphipods in the diet of herring in the Barents Sea is equal to the reported mean diet fraction.	**1988:2021**	We assume that the mean diet fraction of amphipods in capelin equals the mean percentage of amphipods in the diet of capelin.	**Pedersen et al., 2021** We have mean diet fraction of capelin. These are added and converted to percentages and use as lower limit.

147	CCopepodBS_ HerringBS Mean	The mean percentage of copepods in the diet of herring in the Barents Sea is equal to the reported mean diet fraction.	1988:2021	We assume that the mean diet fraction of copepods in capelin equals the mean percentage of copepods in the diet of capelin.	**Pedersen et al., 2021** We have mean diet fraction of capelin. These are added and converted to percentages and use as lower limit.

8.4.5.5 Other demersal fish

148	CCapelinBS_ OtherDemersal BS FractionUpper	The upper percentage of capelin in the diet of other demersal fish is equal to the reported mean diet fraction plus one in the logit space.	1988:2021	We assume that the mean diet fraction of capelin in other demersal fish plus one in the logit space equals the upper limit of the percentage of capelin in the diet of other demersal fish.	**Pedersen et al., 2021** We have mean diet fraction of other demersal fish. These are added and converted to percentages and use as upper limit.
149	CKrillBS_ OtherDemersal BS FractionUpper	The upper percentage of krill in the diet of other demersal fish is equal to the reported mean diet fraction plus one in the logit space.	1988:2021	We assume that the mean diet fraction of krill in other demersal fish plus one in the logit space equals the upper limit of the percentage of krill in the diet of other demersal fish.	**Pedersen et al., 2021** We have mean diet fraction of other demersal fish. These are added and converted to percentages and use as upper limit.
150	CPolarCodBS_	The upper percentage of polar cod in the diet of other demersal fish is	1988:2021	We assume that the mean diet fraction of polar cod in other demersal fish plus one in the logit space equals the upper	**Pedersen et al., 2021**

	OtherDemersal BS FractionUpper	equal to the reported mean diet fraction plus one in the logit space.		limit of the percentage of polar cod in the diet of other demersal fish.	We have mean diet fraction of other demersal fish. These are added and converted to percentages and use as upper limit.
151	CCodBS_ OtherDemersal BS FractionUpper	The upper percentage of cod in the diet of other demersal fish is equal to the reported mean diet fraction plus one in the logit space.	1988:2021	We assume that the mean diet fraction of cod in other demersal fish plus one in the logit space equals the upper limit of the percentage of cod in the diet of other demersal fish.	Pedersen et al., 2021 We have mean diet fraction of other demersal fish. These are added and converted to percentages and use as upper limit.
152	COtherDemersa lBS_OtherDeme rsalBS FractionUpper	The upper percentage of other demersal fish in the diet of other demersal fish is equal to the reported mean diet fraction plus one in the logit space.	1988:2021	We assume that the mean diet fraction of other demersal fish in other demersal fish plus one in the logit space equals the upper limit of the percentage of other demersal fish in the diet of other demersal fish.	Pedersen et al., 2021 We have mean diet fraction of other demersal fish. These are added and converted to percentages and use as upper limit.
153	CHerringBS_ OtherDemersal BS FractionUpper	The upper percentage of herring in the Barents Sea in the diet of other demersal fish is equal to the reported mean diet fraction plus one in the logit space.	1988:2021	We assume that the mean diet fraction of herring in other demersal fish plus one in the logit space equals the upper limit of the percentage of herring in the diet of other demersal fish.	Pedersen et al., 2021 We have mean diet fraction of other demersal fish. These are added and converted to percentages and use as upper limit.

Row	Name	Constraints	Time-period	Description	References
154	CBenthosBS_ OtherDemersal BS FractionUpper	The upper percentage of benthic organisms in the diet of other demersal fish is equal to the reported mean diet fraction plus one in the logit space.	1988:2021	We assume that the mean diet fraction of benthic organisms in other demersal fish plus one in the logit space equals the upper limit of the percentage of benthic organisms in the diet of other demersal fish.	**Pedersen et al., 2021** We have mean diet fraction of other demersal fish. These are added and converted to percentages and use as upper limit.
155	CCopepodsBS_ OtherDemersal BS FractionUpper	The upper percentage of copepods in the diet of other demersal fish is equal to the reported mean diet fraction plus one in the logit space.	1988:2021	We assume that the mean diet fraction of copepods in other demersal fish plus one in the logit space equals the upper limit of the percentage of copepods in the diet of other demersal fish.	**Pedersen et al., 2021** We have mean diet fraction of other demersal fish. These are added and converted to percentages and use as upper limit.

8.4.6 Consumption and diet of marine mammals

8.4.6.1 Minke whale

Row	Name	Constraints	Time-period	Description	References
156	CMinkeWhale Mean ConsumptionHi gh	The mean upper consumption of minke whale is equal to the reported mean annual upper consumption.	1988:2021	We assume that the 95% confidence interval for mean annual consumption of minke whale given in 1000 tonnes are equal to the mean upper bound of consumption.	**Skern-Mauritzen et al., 2022** We have mean annual consumption for minke whale with 95% confidence interval. We use

					this as the upper limit for mean upper consumption.
157	CMinkeWhale Mean ConsumptionLow	The mean lower consumption of minke whale is equal to the reported mean annual lower consumption.	1988:2021	We assume that the 95% confidence interval for mean annual consumption of minke whale given in 1000 tonnes are equal to the mean lower bound of consumption.	**Skern-Mauritzen et al., 2022** We have mean annual consumption for minke whale with 95% confidence interval. We use this as the lower limit for mean lower consumption.
158	COutsideResources_MinkeWhaleUpper	The upper diet percentage of outside resources is at most 25% of the total diet of minke whale.	1988:2021	We assume that minke whale consume at most 25% of their consumption outside of the model domain.	**Based on personal communication with Ulf Lindstrøm.**
159	CBlueWhitingNS_ MinkeWhale FractionUpper	The upper percentage of blue whiting in the diet of minke whale is equal to the reported mean annual diet fraction plus one in the logit space.	1988:2021	We assume that the mean diet fraction of blue whiting in minke whale plus one in the logit space equals the upper limit of the percentage of blue whiting in the diet of minke whale.	**Skern-Mauritzen et al., 2022** We have the mean diet composition of minke whale. We use this as the mean diet composition for the minke whale.
160	CHerringNS_B S_ MinkeWhale FractionUpper	The upper percentage of herring in the diet of minke whale is equal to the reported mean annual diet fraction plus one in the logit space.	1988:2021	We assume that the mean diet fraction of herring in minke whale plus one in the logit space equals the upper limit of the percentage of herring in the diet of minke whale.	**Skern-Mauritzen et al., 2022** We have the mean diet composition of minke whale. We use this as the mean diet composition for the minke whale.

161	CCapelinBS_ MinkeWhale FractionUpper	The upper percentage of capelin in the diet of minke whale is equal to the reported mean annual diet fraction plus one in the logit space.	1988:1991, 1996:2021	We assume that the mean diet fraction of herring in minke whale plus one in the logit space equals the upper limit of the percentage of herring in the diet of minke whale.	**Skern-Mauritzen et al., 2022** We have the mean diet composition of minke whale. We use this as the mean diet composition for the minke whale.
162	CCodBS_OD_ MinkeWhale FractionUpper	The upper percentage of cod and other demersal fish in the diet of minke whale is equal to the reported mean annual diet fraction plus one in the logit space.	1988:1991, 1996:2021	We assume that the mean diet fraction of cod and other demersal fish in minke whale plus one in the logit space equals the upper limit of the percentage of cod and other demersal fish in the diet of minke whale.	**Skern-Mauritzen et al., 2022** We have the mean diet composition of minke whale. We use this as the mean diet composition for the minke whale.
163	CKrillNS_BS_ MinkeWhale FractionUpper	The upper percentage of krill in the diet of minke whale is equal to the reported mean annual diet fraction plus one in the logit space.	1988:2021	We assume that the mean diet fraction of krill in minke whale plus one in the logit space equals the upper limit of the percentage of krill in the diet of minke whale.	**Skern-Mauritzen et al., 2022** We have the mean diet composition of minke whale. We use this as the mean diet composition for the minke whale.
164	CMinkeWhaleT otal Consumption 92-95Upper	The upper limit of the total consumption of percentage of minke whale is equal to the reported total consumption with an uncertainty of 120%	1992:1995	We assume that the total consumption reported in Bogstad et al., 2000 with an uncertainty of 120% is equal to the upper limit of consumption for minke whale for the period 1992-1995.	**Bogstad et al. (2000)** We have total consumption of minke whale in the period of 1992 till 1995.

165	CCapelinBS_ MinkeWhaleFraction92-95Upper	The upper percentage of capelin in the diet of minke whale is equal to the reported mean annual diet fraction plus one in the logit space.	1992:1995	We assume that the percentage of annual consumption of capelin in the diet of minke whale in 1992 till 1995 plus one in the logit space equals the upper limit of capelin in the diet of minke whale.	**Bogstad et al. (2000)** We have annual consumption of minke whale for 1992:1995. This is converted to percentage and used for the period of 1992 till 1995
166	CCodBS_ MinkeWhaleFraction92-95Upper	The upper percentage of cod in the diet of minke whale is equal to the reported mean annual diet fraction plus one in the logit space.	1992:1995	We assume that the percentage of annual consumption of cod in the diet of minke whale in 1992 till 1995 plus one in the logit space equals the upper limit of cod in the diet of minke whale.	**Bogstad et al. (2000)** We have annual consumption of minke whale for 1992:1995. This is converted to percentage and used for the period of 1992 till 1995
167	CODBS_ MinkeWhaleFraction92-95Upper	The upper percentage of other demersal fish in the diet of minke whale is equal to the reported mean annual diet fraction of haddock plus one in the logit space.	1992:1995	We assume that the percentage of annual consumption of haddock in the diet of minke whale in 1992 till 1995 plus one in the logit space equals the upper limit of other demersal fish in the diet of minke whale.	**Bogstad et al. (2000)** We have annual consumption of minke whale for 1992:1995. This is converted to percentage and used for the period of 1992 till 1995
168	CHerringBS_ MinkeWhaleFraction92-95Upper	The upper percentage of herring in the Barents Sea in the diet of minke whale is equal to the reported mean annual diet fraction plus one in the logit space.	1992:1995	We assume that the percentage of annual consumption of herring in the Barents Sea in the diet of minke whale in 1992 till 1995 plus one in the logit space equals the upper limit of herring in the Barents Sea in the diet of minke whale.	**Bogstad et al. (2000)** We have annual consumption of minke whale for 1992:1995. This is converted to percentage and used for the period of 1992 till 1995

| 169 | CKrillBS_ MinkeWhaleFraction92-95Upper | The upper percentage of krill in the Barents Sea in the diet of minke whale is equal to the reported mean annual diet fraction plus one in the logit space. | 1992:1995 | We assume that the percentage of annual consumption of krill in the Barents Sea in the diet of minke whale in 1992 till 1995 plus one in the logit space equals the upper limit of krill in the Barents Sea in the diet of minke whale. | **Bogstad et al. (2000)**

We have annual consumption of minke whale for 1992:1995. This is converted to percentage and used for the period of 1992 till 1995 |

8.4.6.2 Toothed whales

170.	CToothedWhaleMeanConsumptionHigh	The mean upper consumption of toothed whales is equal to the reported mean annual upper consumption.	1988:2021	We assume that the 95% confidence interval for mean annual consumption of toothed whales given in 1000 tonnes are equal to the mean upper bound of consumption.	**Skern-Mauritzen et al., 2022** We have mean annual consumption for toothed whales with 95% confidence interval. We use this as the upper limit for mean upper consumption.
171	CToothedWhaleMeanConsumptionHigh	The mean lower consumption of toothed whales is equal to the reported mean annual lower consumption.	1988:2021	We assume that the 95% confidence interval for mean annual consumption of toothed whales given in 1000 tonnes are equal to the mean lower bound of consumption.	**Skern-Mauritzen et al., 2022** We have mean annual consumption for toothed whales with 95% confidence interval. We use this as the lower limit for mean lower consumption.
172	COutsideResources_	The upper diet percentage of outside resources toothed whales is at most	1988:2021	We assume that toothed whales consume at most 30% of their	**Based on personal communication with Ulf Lindstrøm.**

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	ToothedWhales Upper	30% of the total diet of toothed whales.		consumption outside of the model domain.	
173	Ccod_OD_ ToothedWhales FractionHigh	The upper percentage of cod and other demersal fish in the diet of toothed whales is equal to the reported mean annual diet fraction plus one in the logit space.	1988:2021	We assume that the mean diet fraction of cod and other demersal fish in toothed whales plus one in the logit space equals the upper limit of the percentage of cod and other demersal fish in the diet of toothed whales.	**Skern-Mauritzen et al., 2022** We have diet composition of all the toothed whale species. We use this in combination with their mean consumption to estimate diet composition for the toothed whales.
174	CCapelin_ ToothedWhales FractionHigh	The upper percentage of capelin in the diet of toothed whales is equal to the reported mean annual diet fraction plus one in the logit space.	1988:2021	We assume that the mean diet fraction of capelin in toothed whales plus one in the logit space equals the upper limit of the percentage of capelin in the diet of toothed whales.	**Skern-Mauritzen et al., 2022** We have diet composition of all the toothed whale species. We use this in combination with their mean consumption to estimate diet composition for the toothed whales.
175	CHerringNS_ ToothedWhales FractionHigh	The upper percentage of herring in the Norwegian Sea in the diet of toothed whales is equal to the reported mean annual diet fraction plus one in the logit space.	1988:2021	We assume that the mean diet fraction of herring in the Norwegian Sea in toothed whales plus one in the logit space equals the upper limit of the percentage of herring in the Norwegian Sea in the diet of toothed whales.	**Skern-Mauritzen et al., 2022** We have diet composition of all the toothed whale species. We use this in combination with their mean consumption to estimate diet composition for the toothed whales.
176	CHerringBS_ ToothedWhales	The upper percentage of herring in the Barents Sea in the diet of toothed whales is equal to the	1988:2021	We assume that the mean diet fraction of herring in the Barents Sea in toothed whales plus one in the logit space equals the upper limit of the percentage	**Skern-Mauritzen et al., 2022** We have diet composition of all the toothed whale species. We use this in combination with

	FractionHigh	reported mean annual diet fraction plus one in the logit space.		of herring in the Barents Sea in the diet of toothed whales.	their mean consumption to estimate diet composition for the toothed whales.
177	CBlueWhitingNS_ ToothedWhales FractionHigh	The upper percentage of blue whiting in the diet of toothed whales is equal to the reported mean annual diet fraction plus one in the logit space.	1988:2021	We assume that the mean diet fraction of blue whiting in toothed whales plus one in the logit space equals the upper limit of the percentage of blue whiting in the diet of toothed whales.	**Skern-Mauritzen et al., 2022** We have diet composition of all the toothed whale species. We use this in combination with their mean consumption to estimate diet composition for the toothed whales.
178	CMackerelNS_ ToothedWhales FractionHigh	The upper percentage of mackerel in the diet of toothed whales is equal to the reported mean annual diet fraction plus one in the logit space.	1988:2021	We assume that the mean diet fraction of mackerel in toothed whales plus one in the logit space equals the upper limit of the percentage of mackerel in the diet of toothed whales.	**Skern-Mauritzen et al., 2022** We have diet composition of all the toothed whale species. We use this in combination with their mean consumption to estimate diet composition for the toothed whales.
179	CPolarCodBS_ ToothedWhales FractionHigh	The upper percentage of polar cod in the diet of toothed whales is equal to the reported mean annual diet fraction plus one in the logit space.	1988:2021	We assume that the mean diet fraction of polar cod in toothed whales plus one in the logit space equals the upper limit of the percentage of polar od in the diet of toothed whales.	**Skern-Mauritzen et al., 2022** We have diet composition of all the toothed whale species. We use this in combination with their mean consumption to estimate diet composition for the toothed whales.
180	CBenthosBS_ ToothedWhales FractionHigh	The upper percentage of benthic organisms in the diet of toothed whales is equal to the reported mean annual diet fraction	1988:2021	We assume that the mean diet fraction of benthic organisms in toothed whales plus one in the logit space equals the upper limit of the percentage of benthic organisms in the diet of toothed whales.	**Skern-Mauritzen et al., 2022** We have diet composition of all the toothed whale species. We use this in combination with

		plus one in the logit space.			their mean consumption to estimate diet composition for the toothed whales.
181	CMesopelagicAnd OtherNS_ ToothedWhales FractionHigh	The upper percentage of mesopelagic organisms and other fish in the Norwegian in the diet of toothed whales is equal to the reported mean annual diet fraction plus one in the logit space.	1988:2021	We assume that the mean diet fraction of mesopelagic organisms and other fish in toothed whales plus one in the logit space equals the upper limit of the percentage of pelagic organisms and other fish in the diet of toothed whales.	**Skern-Mauritzen et al., 2022** We have diet composition of all the toothed whale species. We use this in combination with their mean consumption to estimate diet composition for the toothed whales.
182	Ccod_OD_ ToothedWhales FractionMeanUpper	The mean upper percentage of cod and other demersal fish in the diet of toothed whales over the entire time-period is equal to the reported mean annual diet plus 0.25 in the logit space.	1988:2021	We assume that the mean upper diet fraction of cod and other demersal fish in toothed whales equals the mean upper percentage of mackerel in the diet of toothed whales plus 0.25 in the logit space.	**Skern-Mauritzen et al., 2022** We have diet composition of all the toothed whale species. We use this in combination with their mean consumption to estimate the mean diet composition for the toothed whales.
183	CCapelin_ ToothedWhales FractionMeanUpper	The mean upper percentage of capelin in the diet of toothed whales over the entire time-period is equal to the reported mean annual diet plus 0.25 in the logit space.	1988:2021	We assume that the mean upper diet fraction of capelin in toothed whales equals the mean upper percentage of capelin in the diet of toothed whales plus 0.25 in the logit space.	**Skern-Mauritzen et al., 2022** We have diet composition of all the toothed whale species. We use this in combination with their mean consumption to estimate the mean diet composition for the toothed whales.

184	CHerringBS_ ToothedWhales FractionMeanUpper	The mean upper percentage of herring in the Barents Sea in the diet of toothed whales over the entire time-period is equal to the reported mean annual diet plus 0.25 in the logit space.	1988:2021	We assume that the mean upper diet fraction of herring in the Barents Sea in toothed whales equals the mean upper percentage of herring in the Barents Sea in the diet of toothed whales plus 0.25 in the logit space.	**Skern-Mauritzen et al., 2022** We have diet composition of all the toothed whale species. We use this in combination with their mean consumption to estimate the mean diet composition for the toothed whales.
185	CBlueWhitingNS_ ToothedWhales FractionMeanUpper	The mean upper percentage of blue whiting in the diet of toothed whales over the entire time-period is equal to the reported mean annual diet plus 0.25 in the logit space.	1988:2021	We assume that the mean upper diet fraction of blue whiting in toothed whales equals the mean upper percentage of blue whiting in the diet of toothed whales plus 0.25 in the logit space.	**Skern-Mauritzen et al., 2022** We have diet composition of all the toothed whale species. We use this in combination with their mean consumption to estimate the mean diet composition for the toothed whales.
186	CMackerelNS_ ToothedWhales FractionMeanUpper	The mean upper percentage of mackerel in the diet of toothed whales over the entire time-period is equal to the reported mean annual diet plus 0.25 in the logit space.	1988:2021	We assume that the mean upper diet fraction of mackerel in toothed whales equals the mean upper percentage of mackerel in the diet of toothed whales plus 0.25 in the logit space.	**Skern-Mauritzen et al., 2022** We have diet composition of all the toothed whale species. We use this in combination with their mean consumption to estimate the mean diet composition for the toothed whales.
187	CPolarCodBS_ ToothedWhales	The mean upper percentage of capelin in the diet of toothed whales	1988:2021	We assume that the mean upper diet fraction of polar cod in toothed whales equals the mean upper percentage of	**Skern-Mauritzen et al., 2022** We have diet composition of all the toothed whale species. We use this in combination with

	FractionMeanUpper	over the entire time-period is equal to the reported mean annual diet plus 0.25 in the logit space.		polar cod in the diet of toothed whales plus 0.25 in the logit space.	their mean consumption to estimate the mean diet composition for the toothed whales.
188	CBenthosBS_ ToothedWhales FractionMeanUpper	The mean upper percentage of benthic organisms in the diet of toothed whales over the entire time-period is equal to the reported mean annual diet plus 0.25 in the logit space.	1988:2021	We assume that the mean upper diet fraction of benthic organisms in toothed whales equals the mean upper percentage of benthic organisms in the diet of toothed whales plus 0.25 in the logit space.	**Skern-Mauritzen et al., 2022** We have diet composition of all the toothed whale species. We use this in combination with their mean consumption to estimate the mean diet composition for the toothed whales.
189	CMesopelagicAnd OtherNS_ ToothedWhales FractionMeanUpper	The mean upper percentage of mesopelagic organisms and other fish in the Norwegian Sea in the diet of toothed whales over the entire time-period is equal to the reported mean annual diet plus 0.25 in the logit space.	1988:2021	We assume that the mean upper diet fraction of mesopelagic organisms and other fish in the Norwegian Sea in toothed whales equals the mean upper percentage of benthic organisms in the diet of toothed whales plus 0.25 in the logit space.	**Skern-Mauritzen et al., 2022** We have diet composition of all the toothed whale species. We use this in combination with their mean consumption to estimate the mean diet composition for the toothed whales.
190	Ccod_OD_ ToothedWhales	The mean lower percentage of cod and other demersal fish in the diet of toothed whales	1988:2021	We assume that the mean lower diet fraction of cod and other demersal fish in toothed whales equals the mean lower percentage of mackerel in the	**Skern-Mauritzen et al., 2022** We have diet composition of all the toothed whale species. We use this in combination with

				diet of toothed whales minus 0.25 in the logit space.	their mean consumption to estimate the mean diet composition for the toothed whales.
	FractionMeanLower	over the entire time-period is equal to the reported mean annual diet minus 0.25 in the logit space.			
191	CCapelin_ ToothedWhales FractionMeanLower	The mean lower percentage of capelin in the diet of toothed whales over the entire time-period is equal to the reported mean annual diet minus 0.25 in the logit space.	1988:2021	We assume that the mean lower diet fraction of capelin in toothed whales equals the mean lower percentage of capelin in the diet of toothed whales minus 0.25 in the logit space.	**Skern-Mauritzen et al., 2022** We have diet composition of all the toothed whale species. We use this in combination with their mean consumption to estimate the mean diet composition for the toothed whales.
192	CHerringBS_ ToothedWhales FractionMeanLower	The mean lower percentage of herring in the Barents Sea in the diet of toothed whales over the entire time-period is equal to the reported mean annual diet minus 0.25 in the logit space.	1988:2021	We assume that the mean lower diet fraction of herring in the Barents Sea in toothed whales equals the mean lower percentage of herring in the Barents Sea in the diet of toothed whales minus 0.25 in the logit space.	**Skern-Mauritzen et al., 2022** We have diet composition of all the toothed whale species. We use this in combination with their mean consumption to estimate the mean diet composition for the toothed whales.
193	CBlueWhitingNS_ ToothedWhales	The mean lower percentage of blue whiting in the diet of toothed whales over the entire time-period is equal to the reported	1988:2021	We assume that the mean lower diet fraction of blue whiting in toothed whales equals the mean lower percentage of blue whiting in the diet of toothed whales minus 0.25 in the logit space.	**Skern-Mauritzen et al., 2022** We have diet composition of all the toothed whale species. We use this in combination with their mean consumption to estimate the mean diet composition for the toothed whales.

	FractionMeanLower	mean annual diet minus 0.25 in the logit space.			
194	CMackerelNS_ ToothedWhales FractionMeanLower	The mean lower percentage of mackerel in the diet of toothed whales over the entire time-period is equal to the reported mean annual diet minus 0.25 in the logit space.	1988:2021	We assume that the mean lower diet fraction of mackerel in toothed whales equals the mean lower percentage of mackerel in the diet of toothed whales minus 0.25 in the logit space.	**Skern-Mauritzen et al., 2022** We have diet composition of all the toothed whale species. We use this in combination with their mean consumption to estimate the mean diet composition for the toothed whales.
195	CPolarCodBS_ ToothedWhales FractionMeanLower	The mean lower percentage of capelin in the diet of toothed whales over the entire time-period is equal to the reported mean annual diet minus 0.25 in the logit space.	1988:2021	We assume that the mean lower diet fraction of polar cod in toothed whales equals the mean lower percentage of polar cod in the diet of toothed whales minus 0.25 in the logit space.	**Skern-Mauritzen et al., 2022** We have diet composition of all the toothed whale species. We use this in combination with their mean consumption to estimate the mean diet composition for the toothed whales.
196	CBenthosBS_ ToothedWhales FractionMeanLower	The mean lower percentage of benthic organisms in the diet of toothed whales over the entire time-period is equal to the reported mean annual diet minus 0.25 in the logit space.	1988:2021	We assume that the mean lower diet fraction of benthic organisms in toothed whales equals the mean lower percentage of benthic organisms in the diet of toothed whales minus 0.25 in the logit space.	**Skern-Mauritzen et al., 2022** We have diet composition of all the toothed whale species. We use this in combination with their mean consumption to estimate the mean diet composition for the toothed whales.

197	CMesopelagicA nd OtherNS_ ToothedWhales FractionMeanLo wer	The mean lower percentage of mesopelagic organisms and other fish in the Norwegian Sea in the diet of toothed whales over the entire time-period is equal to the reported mean annual diet minus 0.25 in the logit space.	**1988:2021**	We assume that the mean lower diet fraction of mesopelagic organisms and other fish in the Norwegian Sea in toothed whales equals the mean lower percentage of benthic organisms in the diet of toothed whales minus 0.25 in the logit space.	**Skern-Mauritzen et al., 2022** We have diet composition of all the toothed whale species. We use this in combination with their mean consumption to estimate the mean diet composition for the toothed whales.
198	CMackerelNS_ ToothedWhales Lower	Flux from mackerel to toothed whales is at least 0.01 MT	**1988:2021**	We decided to put a minimum consumption of mackerel by marine mammals. This consumption is set to 10 000 tons per year.	**Planque et al., 2022** This was an assumption
199	CBlueWhitingN S_ ToothedWhales Lower	Flux from blue whiting to toothed whales is at least 0.01 MT	**1988:2021**	We decided to put a minimum consumption of blue whiting by marine mammals. This consumption is set to 10 000 tons per year.	**Planque et al., 2022** This was an assumption

8.4.6.3   Other baleen whales

200	COtherBaleenW haleMeanConsu	The mean upper consumption of other baleen whales is equal to	**1988:2021**	We assume that the 95% confidence interval for mean annual consumption of other baleen whales given in 1000	**Skern-Mauritzen et al., 2022**

	mption High	the reported mean annual upper consumption.		tonnes are equal to the mean upper bound of consumption.	We have mean annual consumption for other baleen whales with 95% confidence interval. We use this as the upper limit for mean upper consumption.
201	COtherBaleenW haleMeanConsu mption Low	The mean lower consumption of other baleen whales is equal to the reported mean annual lower consumption.	1988:2021	We assume that the 95% confidence interval for mean annual consumption of other baleen whales given in 1000 tonnes are equal to the mean lower bound of consumption.	**Skern-Mauritzen et al., 2022** We have mean annual consumption for other baleen whales with 95% confidence interval. We use this as the lower limit for mean lower consumption.
202	COutsideResour ces_OtherBalee nWhales Upper	The upper diet percentage of outside resources in other baleen whales is at most 25% of the total diet of other baleen whale.	1988:2021	We assume that other baleen whales consume at most 25% of their consumption outside of the model domain.	**Based on personal communication with Ulf Lindstrøm.**
203	CCapelinBS_ OtherBaleenWh ales FractionUpper	The upper percentage of capelin in the diet of other baleen whales is equal to the reported mean annual diet fraction plus one in the logit space.	1988:2021	We assume that the mean diet fraction of capelin in other baleen whales plus one in the logit space equals the upper limit of the percentage of capelin in the diet of other baleen whales.	**Skern-Mauritzen et al., 2022** We have diet composition of all the other baleen whale species. We use this in combination with their mean consumption to estimate diet composition for the other baleen whales.
204	CHerringNS_ OtherBaleenWh ales	The upper percentage of herring in the Norwegian Sea in the diet of other baleen whales is equal to the reported mean annual	1988:2021	We assume that the mean diet fraction of herring in the Norwegian Sea in other baleen whales plus one in the logit space equals the upper limit of the	**Skern-Mauritzen et al., 2022** We have diet composition of all the other baleen whale species. We use this in combination with their mean consumption to

	FractionUpper	diet fraction plus one in the logit space.		percentage of herring in the Norwegian Sea in the diet of other baleen whales.	estimate diet composition for the other baleen whales.
205	CHerringBS_ OtherBaleenWh ales FractionUpper	The upper percentage of herring in the Barents Sea in the diet of other baleen whales is equal to the reported mean annual diet fraction plus one in the logit space.	1988:2021	We assume that the mean diet fraction of herring in the Barents Sea in other baleen whales plus one in the logit space equals the upper limit of the percentage of herring in the Barents Sea in the diet of other baleen whales.	**Skern-Mauritzen et al., 2022** We have diet composition of all the other baleen whale species. We use this in combination with their mean consumption to estimate diet composition for the other baleen whales.
206	CKrill_ OtherBaleenWh ales FractionUpper	The upper percentage of krill in the diet of other baleen whales is equal to the reported mean annual diet fraction plus one in the logit space.	1988:2021	We assume that the mean diet fraction of krill in other baleen whales plus one in the logit space equals the upper limit of the percentage of krill in the diet of other baleen whales.	**Skern-Mauritzen et al., 2022** We have diet composition of all the other baleen whale species. We use this in combination with their mean consumption to estimate diet composition for the other baleen whales.
207	CCopepodsBS_ OtherBaleenWh ales FractionUpper	The upper percentage of copepods in the diet of other baleen whales is equal to the reported mean annual diet fraction plus one in the logit space.	1988:2021	We assume that the mean diet fraction of copepods in other baleen whales plus one in the logit space equals the upper limit of the percentage of copepods in the diet of other baleen whales.	**Skern-Mauritzen et al., 2022** We have diet composition of all the other baleen whale species. We use this in combination with their mean consumption to estimate diet composition for the other baleen whales.
208	CCapelinBS_ OtherBaleenWh ales	The mean upper percentage of capelin in the diet of other baleen whales over the entire	1988:2021	We assume that the mean upper diet fraction of capelin in other baleen whales equals the mean percentage of	**Skern-Mauritzen et al., 2022** We have diet composition of all the other baleen whale species. We use this in

	FractionMeanUpper	time-period is equal to the reported mean annual diet plus 0.25 in the logit space.		capelin in the diet of other baleen whales plus 0.25 in the logit space.	combination with their mean consumption to estimate the mean diet composition for the other baleen whales.
209	CHerringNS_OtherBaleenWhales FractionMeanUpper	The mean upper percentage of herring in the Norwegian Sea in the diet of other baleen whales over the entire time-period is equal to the reported mean annual diet plus 0.25 in the logit space.	1988:2021	We assume that the mean upper diet fraction of herring in the Norwegian Sea in other baleen whales equals the mean percentage of herring in the Norwegian Sea in the diet of other baleen whales plus 0.25 in the logit space.	**Skern-Mauritzen et al., 2022** We have diet composition of all the other baleen whale species. We use this in combination with their mean consumption to estimate the mean diet composition for the other baleen whales.
210	CHerringBS_OtherBaleenWhales FractionMeanUpper	The mean upper percentage of herring in the Barents Sea in the diet of other baleen whales over the entire time-period is equal to the reported mean annual diet plus 0.25 in the logit space.	1988:2021	We assume that the mean upper diet fraction of herring in the Barents Sea in other baleen whales equals the mean percentage of herring in the Barents Sea in the diet of other baleen whales plus 0.25 in the logit space.	**Skern-Mauritzen et al., 2022** We have diet composition of all the other baleen whale species. We use this in combination with their mean consumption to estimate the mean diet composition for the other baleen whales.
211	CKrill_OtherBaleenWhales	The mean upper percentage of krill in the diet of other baleen whales over the entire time-period is equal to the	1988:2021	We assume that the mean upper diet fraction of krill in other baleen whales equals the mean percentage of krill in the diet of other baleen whales plus 0.25 in the logit space.	**Skern-Mauritzen et al., 2022** We have diet composition of all the other baleen whale species. We use this in combination with their mean consumption to

	FractionMeanUpper	reported mean annual diet plus 0.25 in the logit space.			estimate the mean diet composition for the other baleen whales.
212	CCopepodsBS_ OtherBaleenWhales FractionMeanUpper	The mean upper percentage of copepods in the diet of other baleen whales over the entire time-period is equal to the reported mean annual diet plus 0.25 in the logit space.	1988:2021	We assume that the mean upper diet fraction of copepods in other baleen whales equals the mean percentage of copepods in the diet of other baleen whales plus 0.25 in the logit space.	**Skern-Mauritzen et al., 2022** We have diet composition of all the other baleen whale species. We use this in combination with their mean consumption to estimate the mean diet composition for the other baleen whales.
213	CCapelinBS_ OtherBaleenWhales FractionMeanLower	The mean lower percentage of capelin in the diet of other baleen whales over the entire time-period is equal to the reported mean annual diet minus 0.25 in the logit space.	1988:2021	We assume that the mean lower diet fraction of capelin in other baleen whales equals the mean percentage of capelin in the diet of other baleen whales minus 0.25 in the logit space.	**Skern-Mauritzen et al., 2022** We have diet composition of all the other baleen whale species. We use this in combination with their mean consumption to estimate the mean diet composition for the other baleen whales.
214	CHerringNS_ OtherBaleenWhales FractionMeanLower	The mean lower percentage of herring in the Norwegian Sea in the diet of other baleen whales over the entire time-period is equal to the reported mean annual diet	1988:2021	We assume that the mean lower diet fraction of herring in the Norwegian Sea in other baleen whales equals the mean percentage of herring in the Norwegian Sea in the diet of other baleen whales minus 0.25 in the logit space.	**Skern-Mauritzen et al., 2022** We have diet composition of all the other baleen whale species. We use this in combination with their mean consumption to estimate the mean diet composition for the other baleen whales.

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		minus 0.25 in the logit space.			
215	CHerringBS_ OtherBaleenWhales FractionMeanLower	The mean lower percentage of herring in the Barents Sea in the diet of other baleen whales over the entire time-period is equal to the reported mean annual diet minus 0.25 in the logit space.	1988:2021	We assume that the mean lower diet fraction of herring in the Barents Sea in other baleen whales equals the mean percentage of herring in the Barents Sea in the diet of other baleen whales minus 0.25 in the logit space.	**Skern-Mauritzen et al., 2022** We have diet composition of all the other baleen whale species. We use this in combination with their mean consumption to estimate the mean diet composition for the other baleen whales.
216	CKrill_ OtherBaleenWhales FractionMeanLower	The mean lower percentage of krill in the diet of other baleen whales over the entire time-period is equal to the reported mean annual diet minus 0.25 in the logit space.	1988:2021	We assume that the mean lower diet fraction of krill in other baleen whales equals the mean percentage of krill in the diet of other baleen whales minus 0.25 in the logit space.	**Skern-Mauritzen et al., 2022** We have diet composition of all the other baleen whale species. We use this in combination with their mean consumption to estimate the mean diet composition for the other baleen whales.
217	CCopepodsBS_ OtherBaleenWhales FractionMeanLower	The mean lower percentage of copepods in the diet of other baleen whales over the entire time-period is equal to the reported mean annual diet minus 0.25 in the logit space.	1988:2021	We assume that the mean lower diet fraction of copepods in other baleen whales equals the mean percentage of copepods in the diet of other baleen whales minus 0.25 in the logit space.	**Skern-Mauritzen et al., 2022** We have diet composition of all the other baleen whale species. We use this in combination with their mean consumption to estimate the mean diet composition for the other baleen whales.

8.4.6.4 Seals

218	CSealMean ConsumptionHigh	The mean upper consumption of seals is equal to the reported mean annual upper consumption.	**1988:2021**	We assume that the 95% confidence interval for mean annual consumption of seals given in 1000 tonnes are equal to the mean upper bound of consumption.	**Skern-Mauritzen et al., 2022** We have mean annual consumption for seals with 95% confidence interval. We use this as the upper limit for mean upper consumption.
219	CSealMean ConsumptionLow	The mean lower consumption of seals is equal to the reported mean annual lower consumption.	**1988:2021**	We assume that the 95% confidence interval for mean annual consumption of seals given in 1000 tonnes are equal to the mean lower bound of consumption.	**Skern-Mauritzen et al., 2022** We have mean annual consumption for seals with 95% confidence interval. We use this as the lower limit for mean lower consumption.
220	COutsideResources_ SealsUpper	The upper diet percentage of outside resources in seals is at most 10% of the total diet of seals.	**1988:2021**	We assume that seals consume at most 10% of their consumption outside of the model domain.	**Based on personal communication with Ulf Lindstrøm.**
221	CCapelin_Seal FractionHigh	The upper percentage of capelin in the diet of seals is equal to the reported mean annual diet fraction plus one in the logit space.	**1988:2021**	We assume that the mean diet fraction of capelin in seals plus one in the logit space equals the upper limit of the percentage of capelin in the diet of seals.	**Skern-Mauritzen et al., 2022** We have diet composition of all the seal species. We use this in combination with their mean consumption to estimate diet composition for the seals.

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222	CPolarCodBS_Seal FractionHigh	The upper percentage of polar cod in the diet of seals is equal to the reported mean annual diet fraction plus one in the logit space.	1988:2021	We assume that the mean diet fraction of polar cod in seals plus one in the logit space equals the upper limit of the percentage of polar cod in the diet of seals.	**Skern-Mauritzen et al., 2022** We have diet composition of all the seal species. We use this in combination with their mean consumption to estimate diet composition for the seals.
223	CHerringBS_Seal FractionHigh	The upper percentage of herring in the Barents Sea in the diet of seals is equal to the reported mean annual diet fraction plus one in the logit space.	1988:2021	We assume that the mean diet fraction of herring in the Barents Sea in seals plus one in the logit space equals the upper limit of the percentage of herring in the Barents Sea in the diet of seals.	**Skern-Mauritzen et al., 2022** We have diet composition of all the seal species. We use this in combination with their mean consumption to estimate diet composition for the seals.
224	CKrill_Seal FractionHigh	The upper percentage of krill in the Barents Sea in the diet of seals is equal to the reported mean annual diet fraction plus one in the logit space.	1988:2021	We assume that the mean diet fraction of krill in the Barents Sea in seals plus one in the logit space equals the upper limit of the percentage of krill in the Barents Sea in the diet of seals.	**Skern-Mauritzen et al., 2022** We have diet composition of all the seal species. We use this in combination with their mean consumption to estimate diet composition for the seals.
225	CAmphipods_Seal FractionHigh	The upper percentage of amphipods in the diet of seals is equal to the reported mean annual diet fraction plus one in the logit space.	1988:2021	We assume that the mean diet fraction of amphipods in seals plus one in the logit space equals the upper limit of the percentage of amphipods in the diet of seals.	**Skern-Mauritzen et al., 2022** We have diet composition of all the seal species. We use this in combination with their mean consumption to estimate diet composition for the seals.

226	CBenthosBS_Seal FractionHigh	The upper percentage of benthic organisms in the diet of seals is equal to the reported mean annual diet fraction plus one in the logit space.	1988:2021	We assume that the mean diet fraction of benthic organisms in seals plus one in the logit space equals the upper limit of the percentage of benthic organisms in the diet of seals.	**Skern-Mauritzen et al., 2022** We have diet composition of all the seal species. We use this in combination with their mean consumption to estimate diet composition for the seals.
227	Ccod_OD_Seal FractionHigh	The upper percentage of cod and other demersal fish in the diet of seals is equal to the reported mean annual diet fraction plus one in the logit space.	1988:2021	We assume that the mean diet fraction of cod and other demersal fish in seals plus one in the logit space equals the upper limit of the percentage of cod and other demersal fish in the diet of seals.	**Skern-Mauritzen et al., 2022** We have diet composition of all the seal species. We use this in combination with their mean consumption to estimate diet composition for the seals.
228	Ccod_OD_Seal FractionMeanUpper	The mean upper percentage of cod and other demersal fish in the diet of seal over the entire time-period is equal to the reported mean annual diet plus 0.25 in the logit space.	1988:2021	We assume that the mean upper diet fraction of cod and other demersal fish in seals equals the mean percentage of cod and other demersal fish in the diet of seals plus 0.25 in the logit space.	**Skern-Mauritzen et al., 2022** We have diet composition of all the seal species. We use this in combination with their mean consumption to estimate the mean diet composition for the seals.
229	CCapelinBS_Seal FractionMeanUpper	The mean upper percentage of capelin in the diet of seal over the entire time-period is equal to the reported	1988:2021	We assume that the mean upper diet fraction of capelin in seals equals the mean percentage of capelin in the diet of seals plus 0.25 in the logit space.	**Skern-Mauritzen et al., 2022** We have diet composition of all the seal species. We use this in combination with their mean consumption to estimate the mean diet composition for the seals.

		mean annual diet plus 0.25 in the logit space.			
230	CPolarCodBS_Seal FractionMeanUpper	The mean upper percentage of polar cod in the diet of seal over the entire time-period is equal to the reported mean annual diet plus 0.25 in the logit space.	**1988:2021**	We assume that the mean upper diet fraction of polar cod in seals equals the mean percentage of polar cod in the diet of seals plus 0.25 in the logit space.	**Skern-Mauritzen et al., 2022** We have diet composition of all the seal species. We use this in combination with their mean consumption to estimate the mean diet composition for the seals.
231	CHerringBS_Seal FractionMeanUpper	The mean upper percentage of herring in the Barents Sea in the diet of seal over the entire time-period is equal to the reported mean annual diet plus 0.25 in the logit space.	**1988:2021**	We assume that the mean upper diet fraction of herring in the Barents Sea in seals equals the mean percentage of herring in the Barents Sea in the diet of seals plus 0.25 in the logit space.	**Skern-Mauritzen et al., 2022** We have diet composition of all the seal species. We use this in combination with their mean consumption to estimate the mean diet composition for the seals.
232	CKrill_Seal FractionMeanUpper	The mean upper percentage of krill in the Barents Sea in the diet of seal over the entire time-period is equal to the reported mean annual diet plus 0.25 in the logit space.	**1988:2021**	We assume that the mean upper diet fraction of krill in the Barents Sea in seals equals the mean percentage of krill in the Barents Sea in the diet of seals plus 0.25 in the logit space.	**Skern-Mauritzen et al., 2022** We have diet composition of all the seal species. We use this in combination with their mean consumption to estimate the mean diet composition for the seals.

233	CAmphipodsBS_SealFractionMeanUpper	The mean upper percentage of amphipods in the diet of seal over the entire time-period is equal to the reported mean annual diet plus 0.25 in the logit space.	1988:2021	We assume that the mean upper diet fraction of amphipods in seals equals the mean percentage of amphipods in the diet of seals plus 0.25 in the logit space.	**Skern-Mauritzen et al., 2022** We have diet composition of all the seal species. We use this in combination with their mean consumption to estimate the mean diet composition for the seals.
234	CBenthosBS_Seal FractionMeanUpper	The mean upper percentage of benthic organisms in the diet of seal over the entire time-period is equal to the reported mean annual diet plus 0.25 in the logit space.	1988:2021	We assume that the mean upper diet fraction of benthic organisms in seals equals the mean percentage of benthic organisms in the diet of seals plus 0.25 in the logit space.	**Skern-Mauritzen et al., 2022** We have diet composition of all the seal species. We use this in combination with their mean consumption to estimate the mean diet composition for the seals.
235	Ccod_OD_ SealFraction MeanLower	The mean lower percentage of cod and other demersal fish in the diet of seal over the entire time-period is equal to the reported mean annual diet minus 0.25 in the logit space.	1988:2021	We assume that the mean lower diet fraction of cod and other demersal fish in seals equals the mean percentage of cod and other demersal fish in the diet of seals minus 0.25 in the logit space.	**Skern-Mauritzen et al., 2022** We have diet composition of all the seal species. We use this in combination with their mean consumption to estimate the mean diet composition for the seals.
236	CCapelinBS_ SealFraction	The mean lower percentage of capelin in the diet of seal over the entire time-period is	1988:2021	We assume that the mean lower diet fraction of capelin in seals equals the mean percentage of capelin in the diet of seals minus 0.25 in the logit space.	**Skern-Mauritzen et al., 2022** We have diet composition of all the seal species. We use this in combination with their

	MeanLower	equal to the reported mean annual diet minus 0.25 in the logit space.			mean consumption to estimate the mean diet composition for the seals.
237	CPolarCodBS_ SealFraction MeanLower	The mean lower percentage of polar cod in the diet of seal over the entire time-period is equal to the reported mean annual diet minus 0.25 in the logit space.	1988:2021	We assume that the mean lower diet fraction of polar cod in seals equals the mean percentage of polar cod in the diet of seals minus 0.25 in the logit space.	**Skern-Mauritzen et al., 2022** We have diet composition of all the seal species. We use this in combination with their mean consumption to estimate the mean diet composition for the seals.
238	CHerringBS_ SealFraction MeanLower	The mean lower percentage of herring in the Barents Sea in the diet of seal over the entire time-period is equal to the reported mean annual diet minus 0.25 in the logit space.	1988:2021	We assume that the mean lower diet fraction of herring in the Barents Sea in seals equals the mean percentage of herring in the Barents Sea in the diet of seals minus 0.25 in the logit space.	**Skern-Mauritzen et al., 2022** We have diet composition of all the seal species. We use this in combination with their mean consumption to estimate the mean diet composition for the seals.
239	CKrill_ SealFraction MeanLower	The mean lower percentage of krill in the Barents Sea in the diet of seal over the entire time-period is equal to the reported mean annual diet minus 0.25 in the logit space.	1988:2021	We assume that the mean lower diet fraction of krill in the Barents Sea in seals equals the mean percentage of krill in the Barents Sea in the diet of seals minus 0.25 in the logit space.	**Skern-Mauritzen et al., 2022** We have diet composition of all the seal species. We use this in combination with their mean consumption to estimate the mean diet composition for the seals.

Row	Name	Constraints	Time-period	Description	References
240	CAmphipodsBS – SealFraction MeanLower	The mean lower percentage of amphipods in the diet of seal over the entire time-period is equal to the reported mean annual diet minus 0.25 in the logit space.	1988:2021	We assume that the mean lower diet fraction of amphipods in seals equals the mean percentage of amphipods in the diet of seals minus 0.25 in the logit space.	**Skern-Mauritzen et al., 2022** We have diet composition of all the seal species. We use this in combination with their mean consumption to estimate the mean diet composition for the seals.
241	CBenthosBS_ SealFraction MeanLower	The mean lower percentage of benthic organisms in the diet of seal over the entire time-period is equal to the reported mean annual diet minus 0.25 in the logit space.	1988:2021	We assume that the mean lower diet fraction of benthic organisms in seals equals the mean percentage of benthic organisms in the diet of seals minus 0.25 in the logit space.	**Skern-Mauritzen et al., 2022** We have diet composition of all the seal species. We use this in combination with their mean consumption to estimate the mean diet composition for the seals.

8.4.7 Consumption by birds

8.4.7.1 Norwegian Sea

Row	Name	Constraints	Time-period	Description	References
242	CPelagicFishNS – Birds	The upper limit of consumption by birds in the Norwegian Sea is equal to the 55% (diet fraction of pelagic fish) of	1988:2021	We assume that the 1 MT equals the total consumption of birds in the Norwegian Sea, additionally the diet fraction of the pelagic fish species by	**Barrett, 2002** Birds' consumption is estimated to 1,24 million tonnes in the Norwegian sea.

	ConsumptionUpper	the reported total consumption from birds.		birds is equal to 55%. This gives a total consumption of 550 thousand tonnes.	$0.8 * 1.24 \simeq 1$ 47% lean fish, 15% fatty fish, 38% invertebrates **Planque et al., 2022** The diet fraction of the pelagic fish species in the diet of birds is 55%.
243	CMackerelNS_BirdsConsumptionLower	The lower limit of consumption of mackerel by birds in the Norwegian Sea is at least 10 thousand tonnes.	**1988:2021**	We assume that the minimum consumption of mackerel by birds is at least 10 thousand tonnes.	**Planque et al., 2022** The minimum consumption of mackerel by birds is at least 10 thousand tonnes. This is an assumption.
244	CBlueWhitingNS_ Birds ConsumptionLower	The lower limit of consumption of blue whiting by birds in the Norwegian Sea is at least 10 thousand tonnes.	**1988:2021**	We assume that the minimum consumption of blue whiting by birds is at least 10 thousand tonnes.	**Planque et al., 2022** The minimum consumption of blue whiting by birds is at least 10 thousand tonnes. This is an assumption.

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245	CHerringNS_Bi rds ConsumptionLo wer	The lower limit of consumption of herring by birds in the Norwegian Sea is at least 10 thousand tonnes.	**1988:2021**	We assume that the minimum consumption of herring by birds is at least 10 thousand tonnes.	**Planque et al., 2022** The minimum consumption of herring by birds is at least 10 thousand tonnes. This is an assumption.

8.4.7.2 Barents Sea

246	CPelagicFishBS _ BirdsConsumpti on Upper	The upper limit of consumption by birds in the Barents Sea is equal to the reported total consumption from birds.	**1988:2021**	The 0.0007 gCm^{-2} multiplied by the area to get the total consumption.	**Pedersen et al., 2021** The input for the model run was set to 0.0007 g C m^{-2}.
247	CBirdsBS ConsumptionMi n	The lower limit of bird consumption is at least 0.01 to force the flow to be above zero.	**1988:2021**	We use this to make the consumption at least 0.01 thousand tonnes as this forces the flux to be positive and not sit at zero.	**Assumption** This is used to make the flow a positive flux.
248	CPolarCodBS_ Birds_DietFracti on	The upper percentage of polar cod in the diet of birds in the Barents Sea is equal to the reported	**1988:2021**	We use the diet fractions from all the bird species presented in Pedersen et al., 2021 to calculate the overall diet fraction based on the average consumption by each species. We assume that this aggregate plus one in	**Pedersen et al., 2021** We have mean diet fraction of birds. These are added and converted to percentages and use as upper limit.

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		mean diet fraction plus one in the logit space.		the logit space equals the upper limit of the diet fraction for polar cod in the diet of birds.	
249	CCapelinBS_Birds_ DietFraction	The upper percentage of capelin in the diet of birds in the Barents Sea is equal to the reported mean diet fraction plus one in the logit space.	1988:2021	We use the diet fractions from all the bird species presented in Pedersen et al., 2021 to calculate the overall diet fraction based on the average consumption by each species. We assume that this aggregate plus one in the logit space equals the upper limit of the diet fraction for capelin in the diet of birds.	**Pedersen et al., 2021** We have mean diet fraction of birds. These are added and converted to percentages and use as upper limit.
250	CHerringBS_Birds_ DietFraction	The upper percentage of herring in the diet of birds in the Barents Sea is equal to the reported mean diet fraction plus one in the logit space.	1988:2021	We use the diet fractions from all the bird species presented in Pedersen et al., 2021 to calculate the overall diet fraction based on the average consumption by each species. We assume that this aggregate plus one in the logit space equals the upper limit of the diet fraction for herring in the diet of birds.	**Pedersen et al., 2021** We have mean diet fraction of birds. These are added and converted to percentages and use as upper limit.

8.4.8 Consumption by outside predation

Row	Name	Constraints	Time-period	Description	References
251	CMackerelNS_OutsidePredation UpperRest	Flux from mackerel to outside predators is at most 7 times more than the flux from mackerel to inside predators.	1988:2006, 2008:2009, 2015:2021	For mackerel, Dommasnes et al. (2001) assumed that 25% of the stocks feeds in the Norwegian Sea during the summer season (50% of the year), and consequently used 0.50*0.25 = 12.5% as the proportion of the stock biomass present in the Norwegian Sea. We assume that the predation on mackerel outside the Norwegian sea is at most 7 times more than its predation in the Norwegian sea.	**Dommasnes et al., 2001** - Ratio of mackerel consumption in/out the Norwegian sea
252	CMackerelNS_OutsidePredation LowerRest	Flux from mackerel to outside predators is at equal to the flux from mackerel to inside predators.	1988:2006, 2008:2009, 2015:2021	For mackerel, Dommasnes et al. (2001) assumed that 25% of the stocks feeds in the Norwegian Sea during the summer season (50% of the year), and consequently used 0.50*0.25 = 12.5% as the proportion of the stock biomass present in the Norwegian Sea. We assume that the predation on mackerel outside the Norwegian sea is at least equal to its predation in the Norwegian sea.	**Dommasnes et al., 2001** - Ratio of mackerel consumption in/out the Norwegian sea

253	CMackerelNS_ OutsidePredatio n Upper07,10-14	Flux from mackerel to outside predators is at most a certain percentage given the proportion of mackerel observed in the Norwegian sea.	**2007, 2010:2014**	We have data on the proportion of mackerel stock in the Norwegian sea. We have used the proportions reported by Nøttestad et al. as an upper bound and half of these values as a lower bound.	**Nøttestad et al., 2016** - Ratio of mackerel consumption in/out the Norwegian sea
254	CMackerelNS_ OutsidePredatio n Lower07,10-14	Flux from mackerel to outside predators is at least a certain percentage given the proportion of mackerel in the Norwegian sea observed.	**2007, 2010:2014**	We have data on the proportion of mackerel stock in the Norwegian sea. We have used the proportions reported by Nøttestad et al. as an upper bound and half of these values as a lower bound.	**Nøttestad et al., 2016** - Ratio of mackerel consumption in/out the Norwegian sea
255	CBlueWhitingN S_ OutsidePredatio n Upper	Flux from blue whiting to outside predators is at least 1.2 times more than the flux from blue whiting to inside predators.	**1988:2021**	Dommasnes has made an estimation of the consumption ratio of blue whiting in and out the Norwegian sea. We assume that the predation on blue whiting outside the Norwegian sea is at most 1.2 times more than its predation in the Norwegian.	**Dommasnes et al., 2001** - Ratio of blue whiting consumption in/out the Norwegian sea
256	CBlueWhitingN S_ OutsidePredatio n Lower	Flux from blue whiting to outside predators is at least 1/1.2 (~0.83) times less than more than the flux from blue whiting to inside predators.	**1988:2021**	Dommasnes has made an estimation of the consumption ratio of blue whiting in and out the Norwegian sea. We assume that the predation on blue whiting outside the Norwegian sea is at least 1/1.2 (~0.83) less than times its predation in the Norwegian.	**Dommasnes et al., 2001** - Ratio of blue whiting consumption in/out the Norwegian sea

8.4.9 Natural mortality

257	CCapelinNatural Mortality	Flux from capelin to benthic organisms is at most 90% of the biomass of capelin	1988:2021	We assume that the spawning mortality can be up to 90% of the biomass of capelin.	Fall et al., 2020 The life history of capelin describes that a capelin dies after spawning.

8.5 Appendix 5 – Summary of flows by predator

Prey	Flow	Proportion in diet
MinkeWhale		
HerringNS	1,729 [1,670;1,900]	0.28 [0.26;0.31]
BlueWhitingNS	610 [597;649]	0.10 [0.09;0.10]
CodBS	74 [65;101]	0.01 [0.01;0.02]
HerringBS	586 [532;745]	0.09 [0.07;0.12]
CapelinBS	476 [431;606]	0.08 [0.06;0.10]
OtherDemersalBS	160 [144;209]	0.03 [0.02;0.04]
KrillNS	867 [800;1,057]	0.14 [0.11;0.17]
KrillBS	826 [760;1,017]	0.13 [0.11;0.16]
OutsideResources	817 [768;959]	0.13 [0.11;0.16]
ToothedWhales		
HerringNS	424 [411;461]	0.12 [0.11;0.14]
BlueWhitingNS	124 [122;132]	0.04 [0.03;0.04]
MackerelNS	92 [90;98]	0.03 [0.02;0.03]
CodBS	127 [114;167]	0.04 [0.03;0.05]
PolarCodBS	244 [235;269]	0.07 [0.06;0.08]
HerringBS	85 [81;97]	0.02 [0.02;0.03]
CapelinBS	367 [355;401]	0.11 [0.10;0.12]
OtherDemersalBS	511 [494;557]	0.15 [0.13;0.16]
MesopelagicAndOtherNS	1,007 [992;1,050]	0.29 [0.27;0.30]
BenthosBS	109 [103;126]	0.03 [0.03;0.04]
OutsideResources	380 [347;476]	0.11 [0.08;0.14]

OtherBaleenWhales

HerringNS	167 [161;184]	0.02 [0.02;0.03]
HerringBS	369 [348;421]	0.05 [0.04;0.06]
CapelinBS	830 [804;908]	0.12 [0.11;0.13]
KrillNS	1,973 [1,830;2,385]	0.28 [0.22;0.34]
KrillBS	1,987 [1,843;2,397]	0.28 [0.23;0.34]
CopepodBS	554 [532;612]	0.08 [0.07;0.09]
OutsideResources	1,158 [1,041;1,511]	0.17 [0.12;0.21]

FPelagic

HerringNS	788 [788;788]	0.26 [0.26;0.26]
BlueWhitingNS	1,098 [1,098;1,098]	0.36 [0.36;0.36]
MackerelNS	793 [793;793]	0.30 [0.30;0.30]
CapelinBS	198 [198;198]	0.07 [0.07;0.07]

Birds

HerringNS	114 [103;144]	0.11 [0.08;0.14]
BlueWhitingNS	240 [227;275]	0.23 [0.19;0.27]
MackerelNS	103 [93;131]	0.10 [0.08;0.13]
PolarCodBS	160 [143;211]	0.14 [0.10;0.18]
HerringBS	288 [264;359]	0.25 [0.20;0.30]
CapelinBS	191 [172;250]	0.17 [0.12;0.21]

OutsidePredation

BlueWhitingNS	3,687 [3,636;3,833]	0.91 [0.9;0.93]
MackerelNS	328 [306;392]	0.09 [0.07;0.1]

CodBS

CodBS	149 [147;156]	0.03 [0.03;0.03]

|		
PolarCodBS	203 [197;220]	0.04 [0.04;0.04]
HerringBS	102 [100;107]	0.02 [0.02;0.02]
CapelinBS	2,176 [2,154;2,239]	0.41 [0.39;0.42]
OtherDemersalBS	256 [251;272]	0.05 [0.05;0.06]
KrillBS	576 [560;617]	0.12 [0.11;0.13]
AmphipodsBS	376 [368;401]	0.09 [0.09;0.10]
BenthosBS	1,187 [1,158;1,272]	0.24 [0.22;0.25]
OtherDemersalBS		
CodBS	58 [52;75]	0.01 [0.01;0.01]
PolarCodBS	153 [140;189]	0.02 [0.02;0.03]
HerringBS	636 [600;743]	0.09 [0.07;0.10]
CapelinBS	379 [349;467]	0.05 [0.04;0.06]
OtherDemersalBS	169 [150;223]	0.02 [0.02;0.03]
KrillBS	4,025 [3,954;4,229]	0.55 [0.52;0.58]
CopepodBS	1,002 [952;1,144]	0.14 [0.12;0.16]
BenthosBS	902 [828;1,120]	0.12 [0.10;0.15]
Seals		
CodBS	102 [90;137]	0.02 [0.01;0.02]
PolarCodBS	879 [862;934]	0.14 [0.14;0.15]
HerringBS	594 [576;643]	0.10 [0.09;0.11]
CapelinBS	541 [516;619]	0.09 [0.08;0.10]
OtherDemersalBS	334 [320;375]	0.06 [0.05;0.06]
KrillBS	386 [376;412]	0.07 [0.06;0.07]
AmphipodsBS	2,227 [2,183;2,351]	0.38 [0.36;0.40]
BenthosBS	589 [560;667]	0.10 [0.09;0.11]
OutsideResources	293 [273;353]	0.05 [0.04;0.06]

FDemersal

CodBS	619 [619;619]	0.64 [0.64;0.64]
OtherDemersalBS	335 [335;335]	0.36 [0.36;0.36]

BenthosBS

CapelinBS	860 [773;1,110]	1 [1;1]

FMinkeWhale

MinkeWhale	3 [3;3]	1 [1;1]

FSeals

Seals	4 [4;4]	1 [1;1]

HerringNS

KrillNS	3,498 [3,346;3,918]	0.21 [0.18;0.23]
ZooPlanktonNS	13,589 [13,363;14,259]	0.79 [0.77;0.82]

BlueWhitingNS

KrillNS	3,648 [3,476;4,111]	0.19 [0.16;0.22]
MesopelagicAndOtherNS	945 [903;1,052]	0.05 [0.04;0.06]
ZooPlanktonNS	5,381 [5,185;5,934]	0.26 [0.24;0.29]
OutsideResources	9,865 [9,770;10,134]	0.50 [0.49;0.51]
KrillNS	3,648 [3,476;4,111]	0.19 [0.16;0.22]

MackerelNS

KrillNS	578 [537;699]	0.05 [0.04;0.06]
ZooPlanktonNS	4,171 [4,099;4,379]	0.35 [0.34;0.37]
OutsideResources	6,827 [6,721;7,129]	0.60 [0.58;0.61]

PolarCodBS

KrillBS	1,121 [1,093;1,206]	0.16 [0.14;0.17]
AmphipodsBS	2,849 [2,784;3,041]	0.38 [0.35;0.41]

CopepodBS	2,695 [2,632;2,881]	0.36 [0.34;0.39]
BenthosBS	819 [797;884]	0.10 [0.09;0.11]
HerringBS		
KrillBS	2,677 [2,620;2,834]	0.29 [0.27;0.30]
AmphipodsBS	191 [187;202]	0.02 [0.02;0.02]
CopepodBS	6,698 [6,557;7,090]	0.69 [0.68;0.71]
CapelinBS		
KrillBS	7,604 [7,301;8,422]	0.45 [0.41;0.49]
CopepodBS	9,252 [8,929;10,196]	0.55 [0.51;0.59]

8.6 Appendix 6 – Fluxes

Reconstructed time series of all the fluxes in the model. The fluxes are ordered by predator. The title shows the Prey_Predator. The fluxes are lagged by one year to the biomass. The biomass in 2021 was caused by biomass in 2020 and the flux of 2020. Minke whale, toothed whales, other baleen whales and seals as predators can be found in the Results

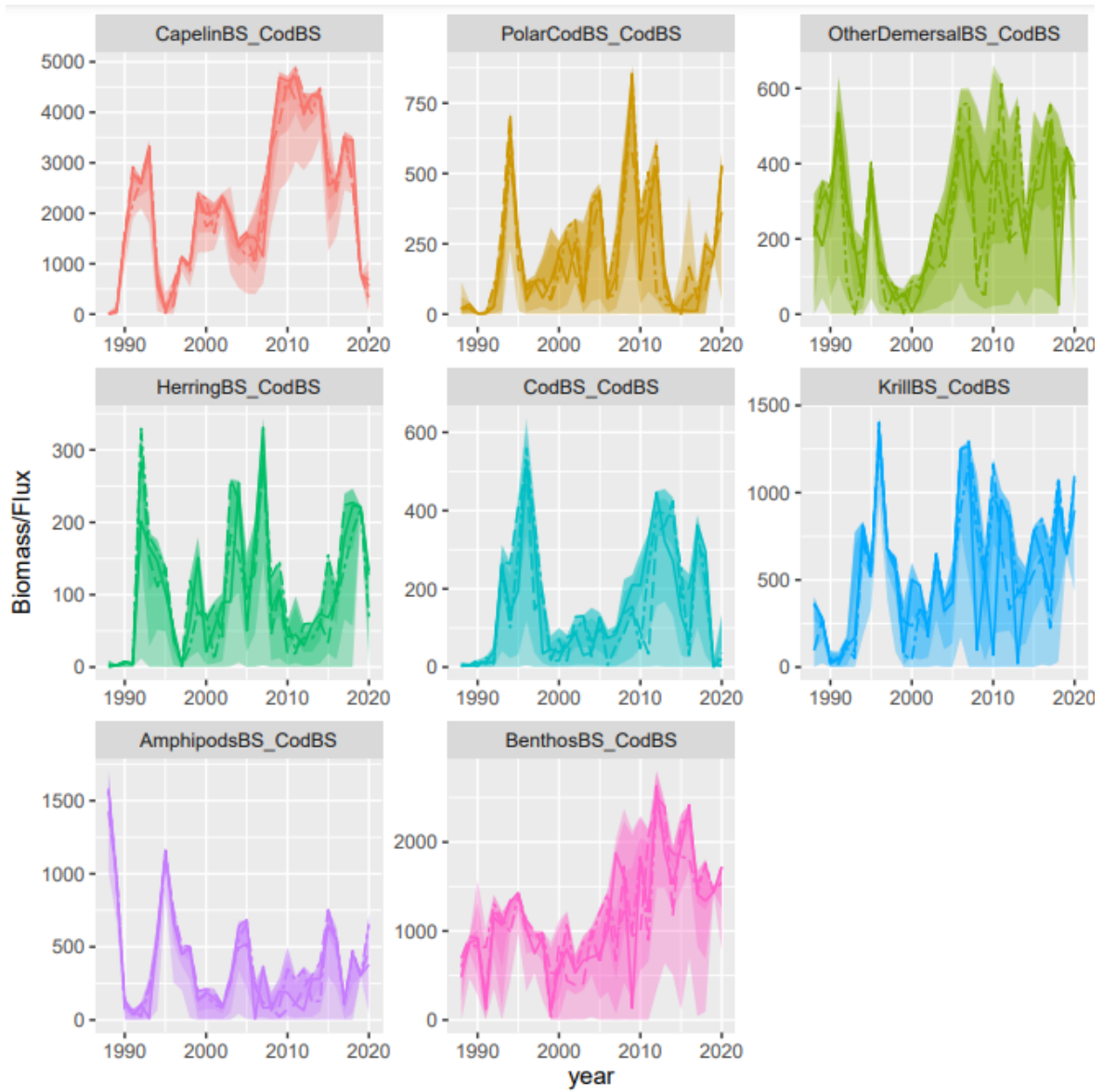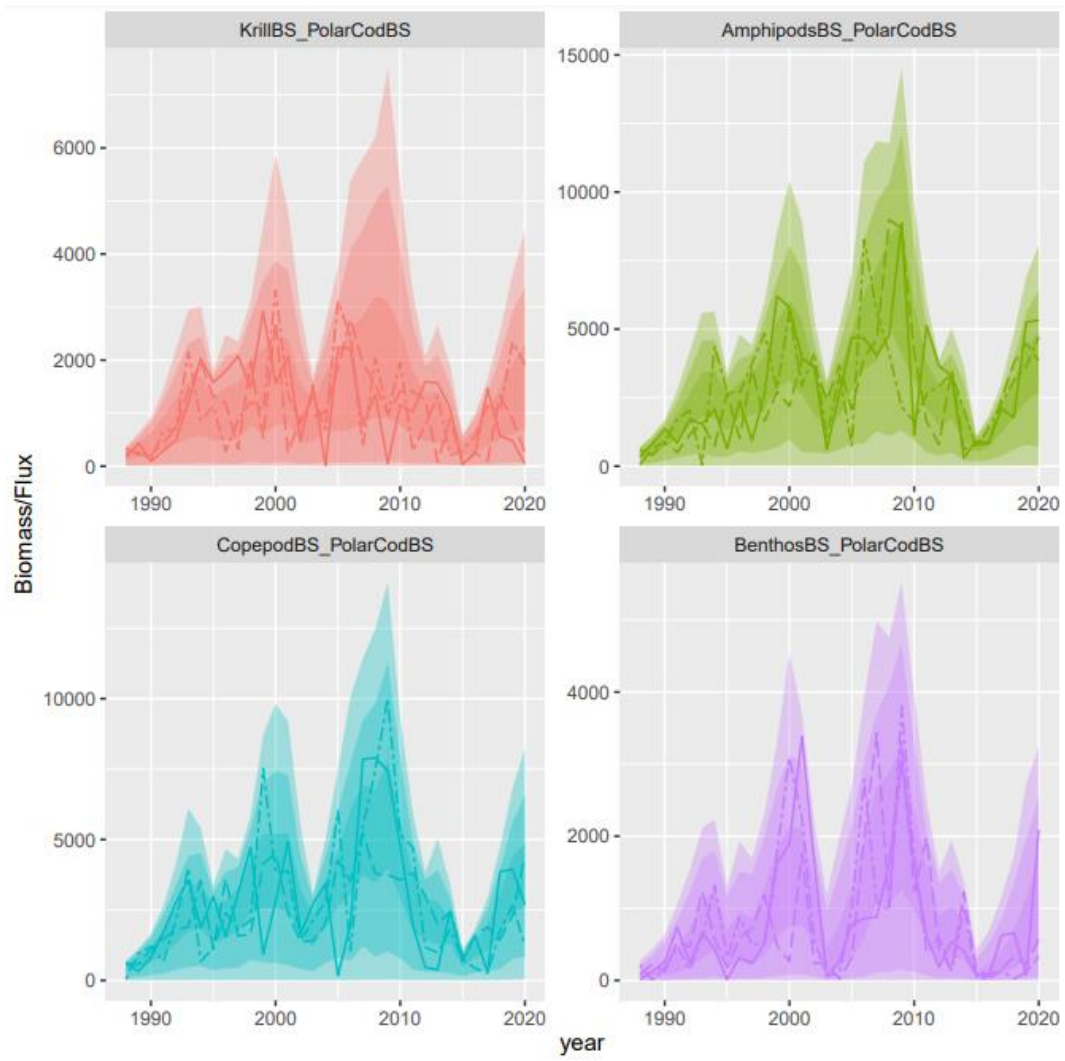### 8.6.1 Norwegian spring spawning herring - Adult
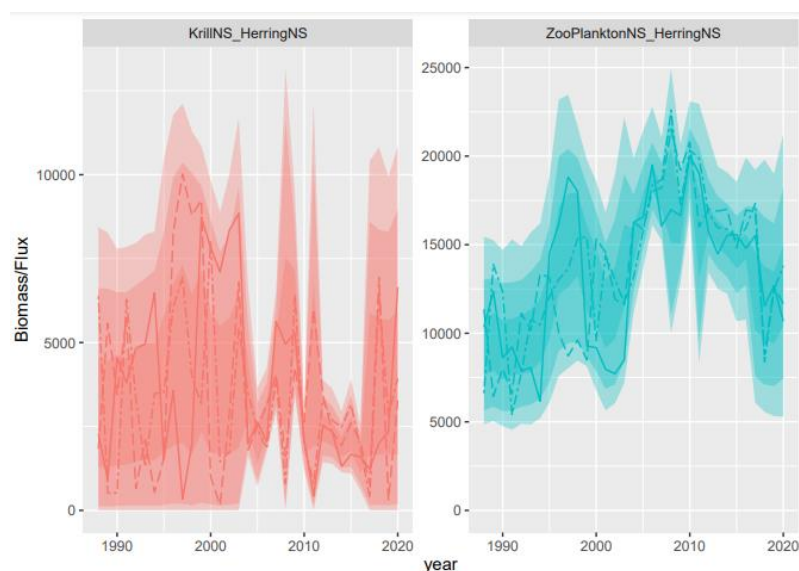
8.6.2 Blue whiting
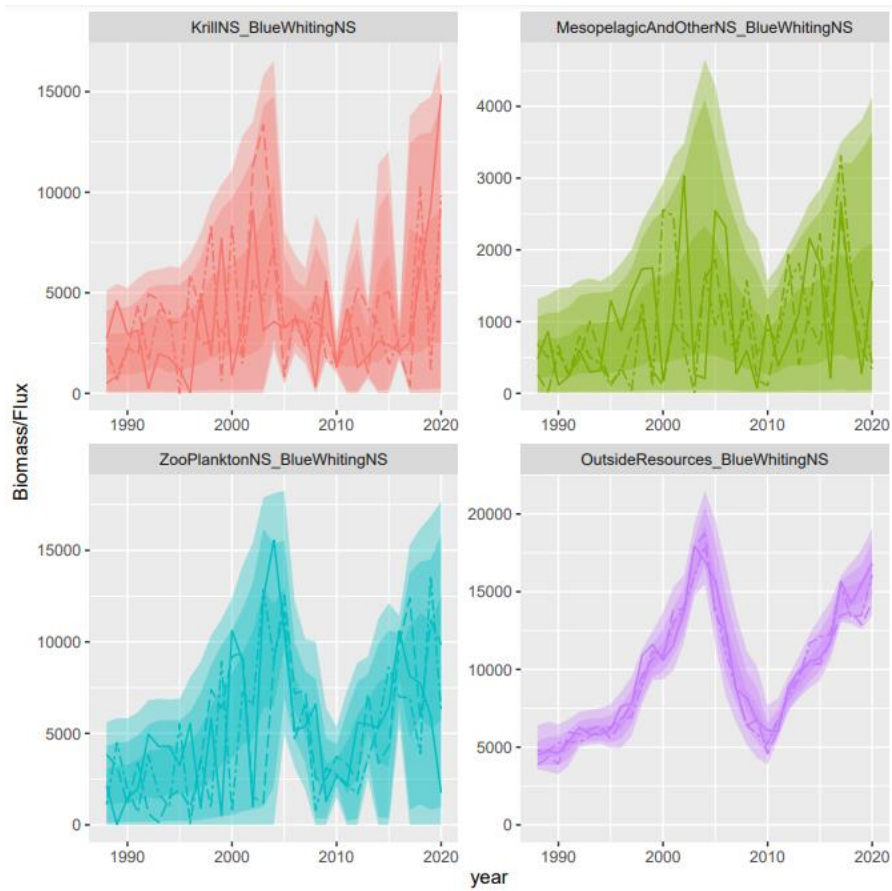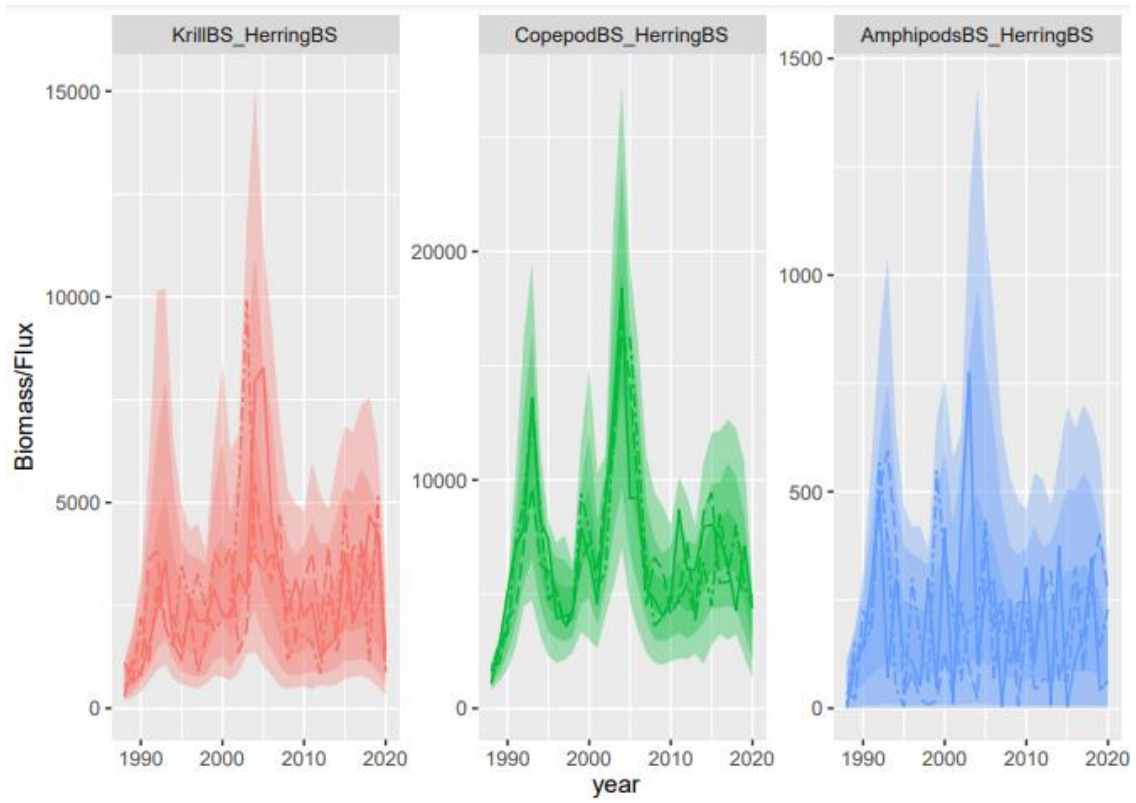

8.6.3 Atlantic mackerel
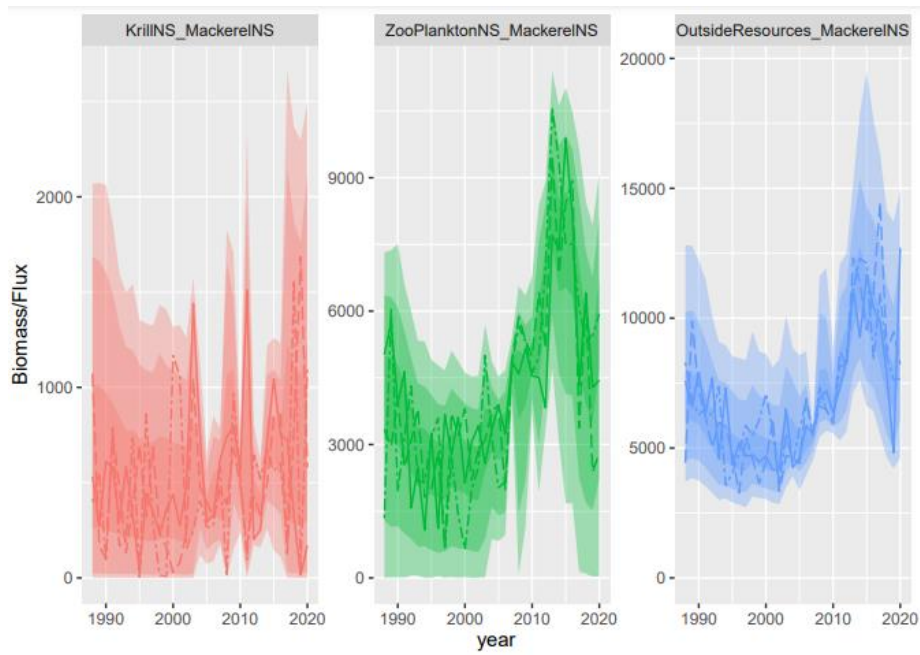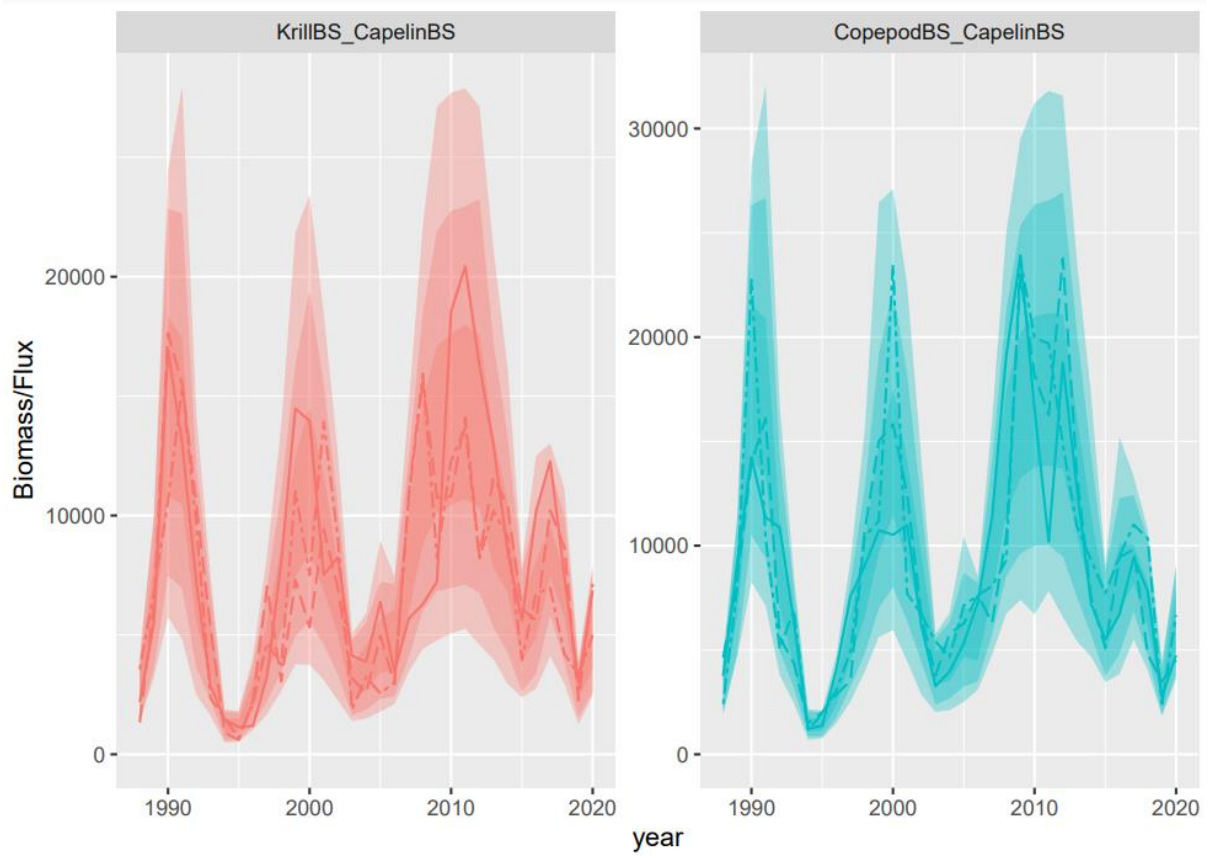
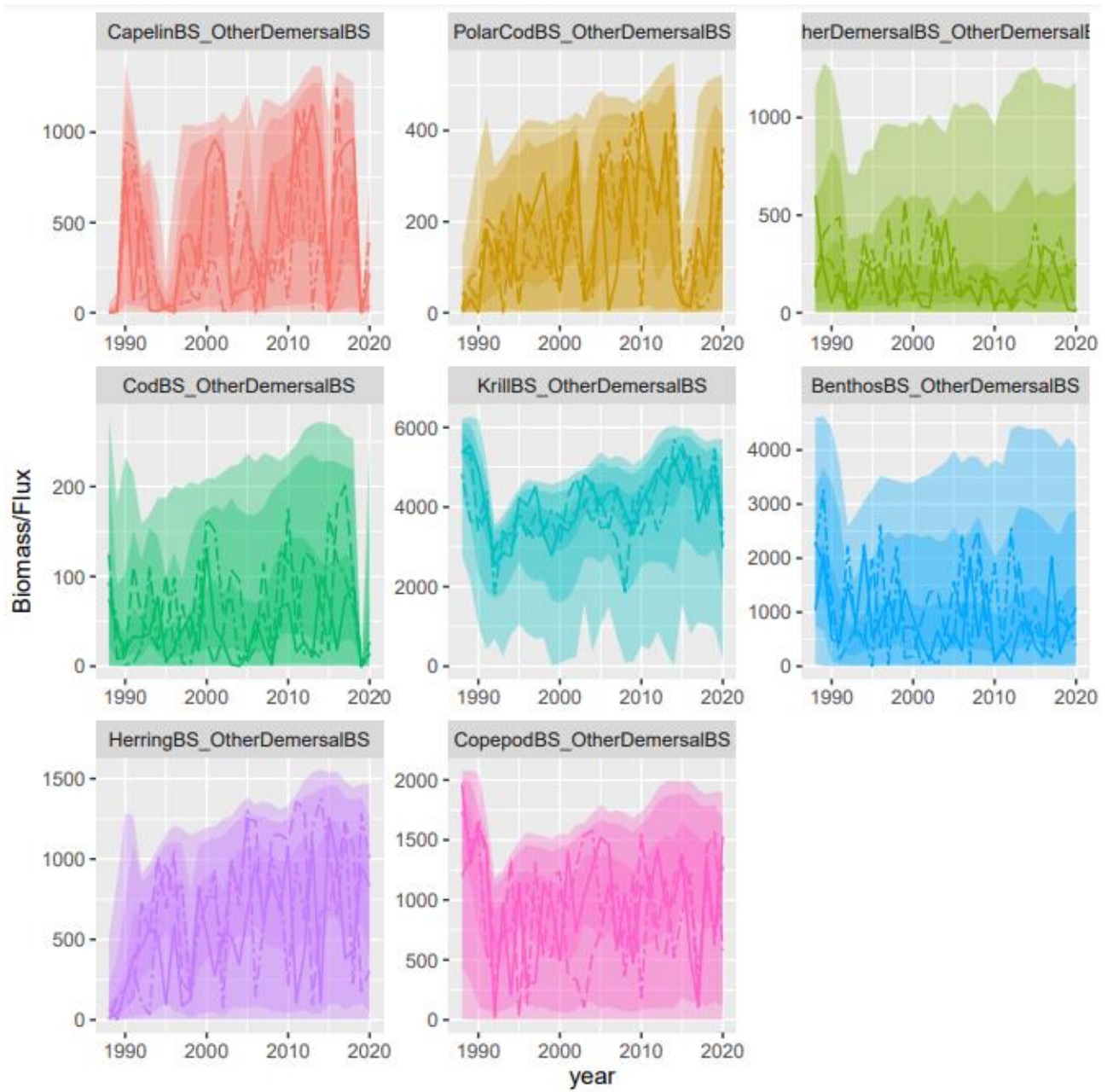## 8.6.4 Atlantic cod

8.6.5 Polar Cod

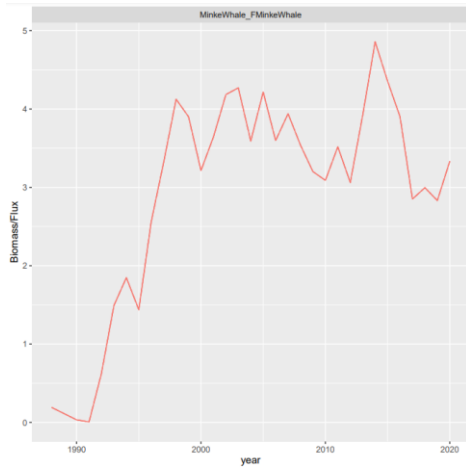## 8.6.6   Norwegian spring spawning herring – Juvenile
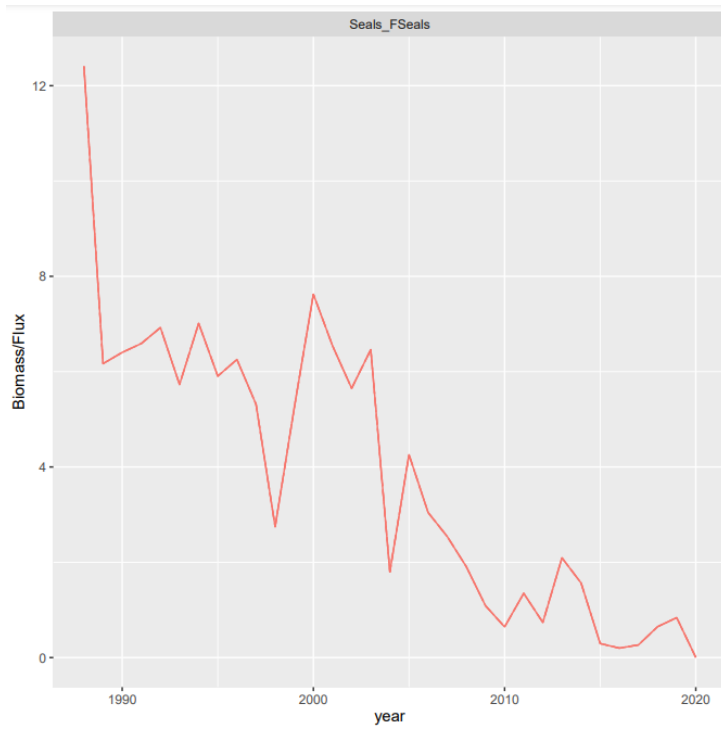
8.6.7   Capelin
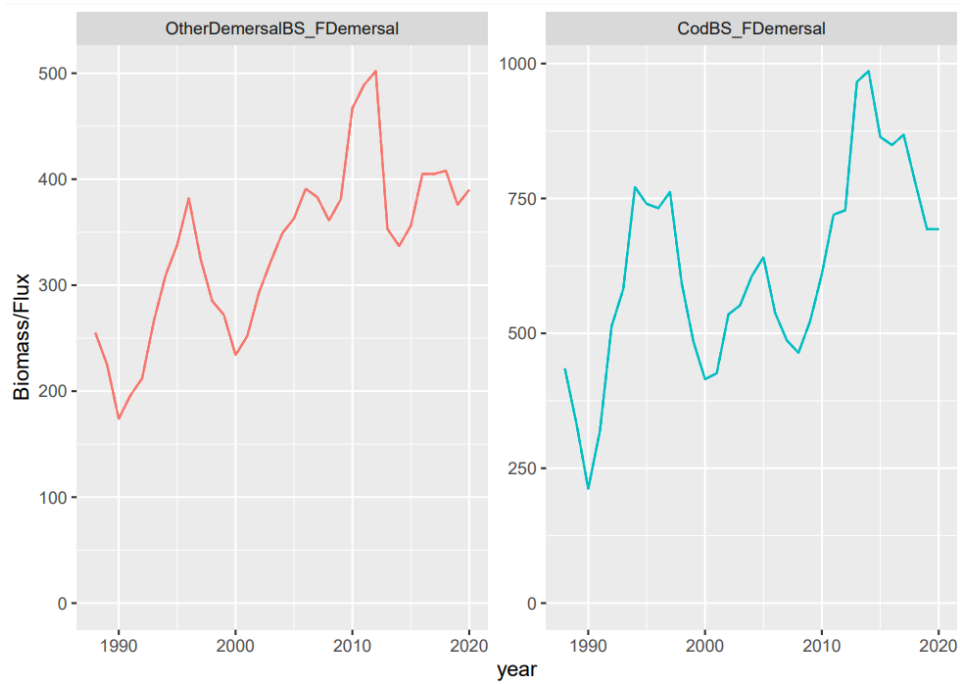
8.6.8   Other demersal fish
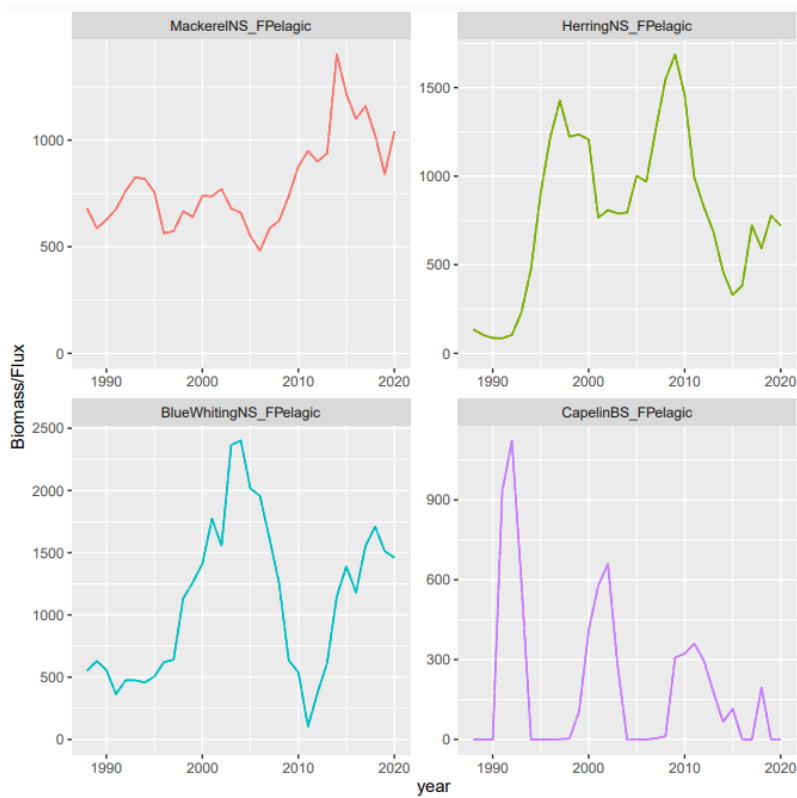
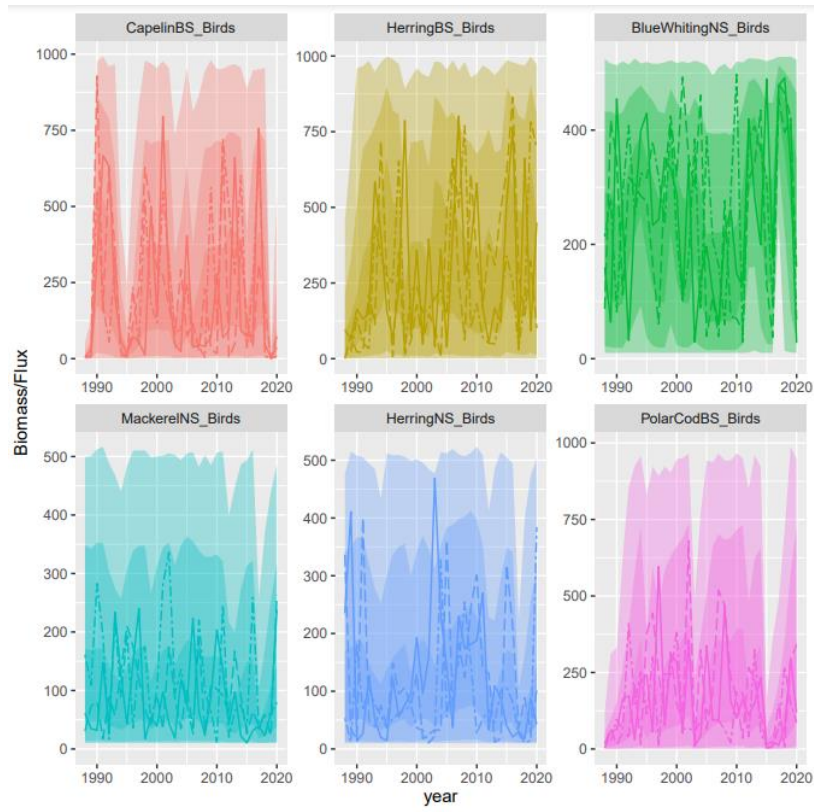## 8.6.9 Minke whale hunting

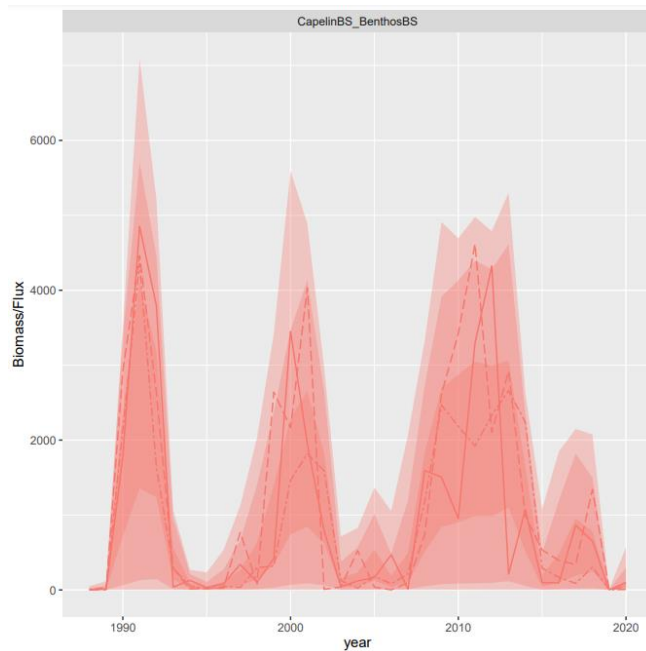## 8.6.10 Seal hunting

8.6.11 Demersal fisheries

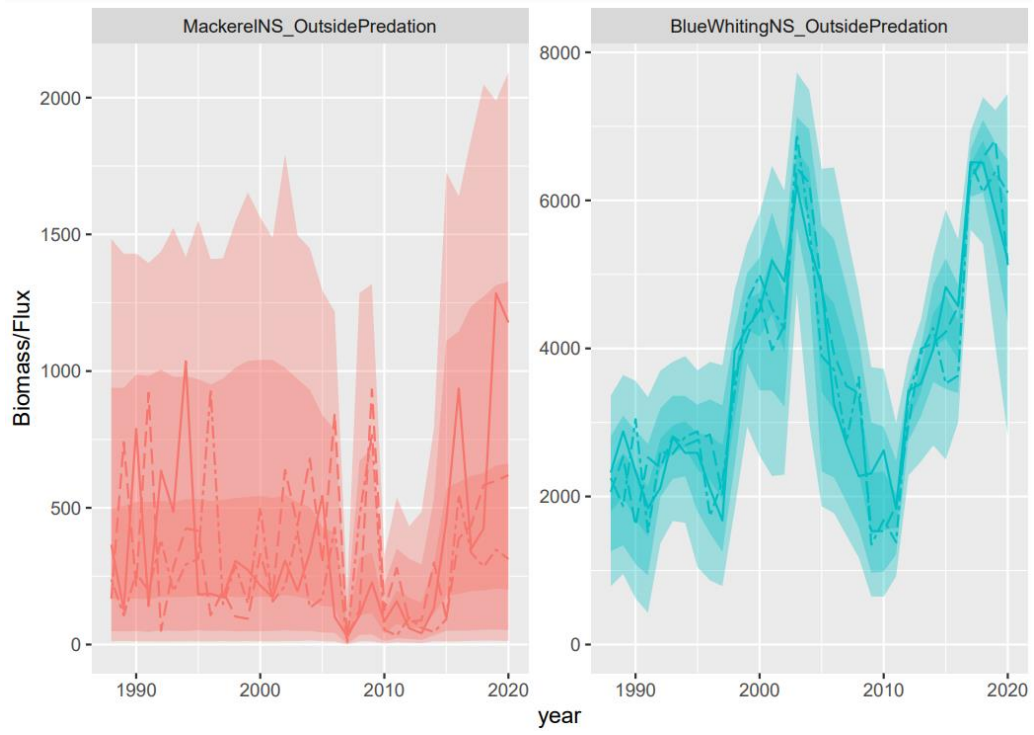## 8.6.12 Pelagic fisheries

191

8.6.13   Birds

8.6.14   Benthos

192

8.6.15   Outside predation

8.7 Appendix 7 – Direct and indirect interactions

The correlation analysis. The output table for each interaction analysed in the model. Each table displays the prey and the predators. The average biomass the group has (in thousand tonnes) and the correlation coefficient between the consumption of the predators of the prey (with 95% confidence interval).

8.7.1 Direct interaction

8.7.1.1 Norwegian Sea

8.7.1.1.1 Marine mammals

Table 10. The direct interaction represented as the correlation between the consumption by marine mammals and fisheries catch through their shared resource, adult and juvenile Norwegian spring spawning herring. The correlation is positive and crosses zero with the 95% confidence interval.

Category	Species	Biomass	Inflow	Correlation [95% CI]
Prey	Adult & juvenile herring	6325	NaN	
Predator 1	Minke whale, toothed whales & other baleen whales	2833	2274	0.12 [-0.10, 0.34]
Predator 2	Pelagic fisheries	0	788	

Table 11. The direct interaction represented as the correlation between the consumption by marine mammals and fisheries catch through their shared resource, adult Norwegian spring spawning herring. The correlation is slightly positive and crosses zero with the 95% confidence interval.

Category	Species	Biomass	Inflow	Correlation [95% CI]
Prey	Adult herring	4577	NaN	
Predator 1	Minke whale, toothed whales & other baleen whales	2573	2320	0.01 [-0.24, 0.27]
Predator 2	Pelagic fisheries	0	788	

Table 12. The direct interaction represented as the correlation between the consumption by marine mammals and fisheries catch through their shared resource, blue whiting. The correlation is positive and crosses zero with the 95% confidence interval.

Category	Species	Biomass	Inflow	Correlation [95% CI]
Prey	Blue whiting	3606	NaN	
Predator 1	Minke whale & toothed whales	1242	735	0.17 [-0.03, 0.37]
Predator 2	Pelagic fisheries	0	893	

Table 13. The direct interaction represented as the correlation between the consumption by marine mammals and fisheries catch through their shared resource, Atlantic mackerel. The correlation is positive and crosses zero with the 95% confidence interval.

Category	Species	Biomass	Inflow	Correlation [95% CI]
Prey	Mackerel	3567	NaN	
Predator 1	Toothed whales	544	92	0.13 [-0.23, 0.47]
Predator 2	Pelagic fisheries	0	793	

Table 14. The direct interaction represented as the correlation between the consumption by marine mammals and fisheries catch through their shared resource in the Norwegian Sea, adult Norwegian spring spawning herring, blue whiting, and Atlantic mackerel. The correlation is positive and crosses zero with the 95% confidence interval.

Category	Species	Biomass	Inflow	Correlation [95% CI]
Prey	Adult herring, blue whiting & mackerel	11750	NaN	
Predator 1	Minke whale, toothed whales & other baleen whales	2573	1550	0.14 [-0.14, 0.39]
Predator 2	Pelagic fisheries	0	893	

8.7.1.1.2 Minke Whale

Table 15. The direct interaction represented as the correlation between the consumption by minke whale and fisheries catch through their shared resource, adult and juvenile Norwegian spring spawning herring. The correlation is positive and crosses zero with the 95% confidence interval.

Category	Species	Biomass	Inflow	Correlation [95% CI]
Prey	Adult & juvenile herring	6325	NaN	
Predator 1	Minke whale	698	1158	0.04 [-0.18, 0.24]
Predator 2	Pelagic fisheries	0	788	

Table 16. The direct interaction represented as the correlation between the consumption by minke whale and fisheries catch through their shared resource, adult Norwegian spring spawning herring. The correlation is slightly positive and crosses zero with the 95% confidence interval.

Category	Species	Biomass	Inflow	Correlation [95% CI]
Prey	Adult herring	4577	NaN	
Predator 1	Minke whale	698	1729	0.00 [-0.25, 0.24]
Predator 2	Pelagic fisheries	0	788	

Table 17. The direct interaction represented as the correlation between the consumption by minke whale and fisheries catch through their shared resource, blue whiting. The correlation is positive and crosses zero with the 95% confidence interval.

Category	Species	Biomass	Inflow	Correlation [95% CI]
Prey	Blue whiting	3606	NaN	
Predator 1	Minke whale	1242	610	0.18 [-0.06, 0.41]
Predator 2	Pelagic fisheries	0	1098	

8.7.1.1.3 Other baleen whales

Table 18. The direct interaction represented as the correlation between the consumption by other baleen whales and fisheries catch through their shared resource, adult and juvenile Norwegian spring spawning herring. The correlation is positive and crosses zero with the 95% confidence interval.

Category	Species	Biomass	Inflow	Correlation [95% CI]
Prey	Adult & juvenile herring	6325	NaN	
Predator 1	Other baleen whale	1331	268	0.17 [-0.15, 0.47]
Predator 2	Pelagic fisheries	0	788	

Table 19. The direct interaction represented as the correlation between the consumption by other baleen whales and fisheries catch through their shared resource, adult Norwegian spring spawning herring. The correlation is slightly positive and crosses zero with the 95% confidence interval.

Category	Species	Biomass	Inflow	Correlation [95% CI]
Prey	Adult herring	4577	NaN	
Predator 1	Other baleen whale	1331	167	0.06 [-0.30, 0.39]
Predator 2	Pelagic fisheries	0	788	

8.7.1.1.4 Toothed whales

Table 20. The direct interaction represented as the correlation between the consumption by toothed whales and fisheries catch through their shared resource, adult and juvenile Norwegian spring spawning herring. The correlation is positive and crosses zero with the 95% confidence interval.

Category	Species	Biomass	Inflow	Correlation [95% CI]
Prey	Adult & juvenile herring	6325	NaN	
Predator 1	Toothed whales	544	255	0.02 [-0.30, 0.36]
Predator 2	Pelagic fisheries	0	788	

Table 21. The direct interaction represented as the correlation between the consumption by toothed whales and fisheries catch through their shared resource, adult Norwegian spring spawning herring. The correlation is slightly positive and crosses zero with the 95% confidence interval.

Category	Species	Biomass	Inflow	Correlation [95% CI]
Prey	Adult herring	4577	NaN	
Predator 1	Toothed whales	544	424	0.02 [-0.31, 0.35]
Predator 2	Pelagic fisheries	0	788	

Table 22. The direct interaction represented as the correlation between the consumption by toothed whales and fisheries catch through their shared resource, blue whiting. The correlation is positive and crosses zero with the 95% confidence interval.

Category	Species	Biomass	Inflow	Correlation [95% CI]
Prey	Blue whiting	3606	NaN	
Predator 1	Toothed whales	544	124	0.08 [-0.20, 0.35]
Predator 2	Pelagic fisheries	0	1098	

Table 23. The direct interaction represented as the correlation between the consumption by toothed whales and fisheries catch through their shared resource, Atlantic mackerel. The correlation is positive and crosses zero with the 95% confidence interval.

Category	Species	Biomass	Inflow	Correlation [95% CI]
Prey	Mackerel	3567	NaN	
Predator 1	Toothed whales	544	92	0.13 [-0.23, 0.47]
Predator 2	Pelagic fisheries	0	793	

8.7.1.2 Barents Sea

8.7.1.2.1 Marine mammals

Table 24. The direct interaction represented as the correlation between the consumption by marine mammals and fisheries catch through their shared resource, Atlantic cod. The correlation is positive.

Category	Species	Biomass	Inflow	Correlation [95% CI]
Prey	Cod	1899	149	
Predator 1	Minke whale, toothed whales, other baleen whales & seals	2833	303	0.22 [0.06, 0.4]
Predator 2	Demersal fisheries	0	619	

Table 25. The direct interaction represented as the correlation between the consumption by marine mammals and fisheries catch through their shared resource, other demersal fish. The correlation is negative.

Category	Species	Biomass	Inflow	Correlation [95% CI]
Prey	Other demersal fish	2331	169	
Predator 1	Minke whale, toothed whales & seals	1502	1005	-0.21 [-0.40, 0.00]
Predator 2	Demersal fisheries	0	335	

Table 26. The direct interaction represented as the correlation between the consumption by marine mammals and fisheries catch through their shared resource, capelin. The correlation is positive.

Category	Species	Biomass	Inflow	Correlation [95% CI]
Prey	Capelin	2342	NaN	
Predator 1	Minke whale, toothed whales, other baleen whales & seals	2833	2214	0.45 [0.29, 0.60]
Predator 2	Pelagic fisheries	0	198	

Table 27. The direct interaction represented as the correlation between the consumption by marine mammals and fisheries catch through their shared resource in the Barents Sea. The correlation is positive.

Category	Species	Biomass	Inflow	Correlation [95% CI]
Prey	Capelin, cod, juvenile herring, polar cod & other demersal fish	9401	856	
Predator 1	Minke whale, toothed whales, other baleen whales & seals	2833	1680	0.44 [0.30, 0.57]
Predator 2	Demersal fisheries & pelagic fisheries	0	675	

8.7.1.2.2   Minke whale

Table 28. The direct interaction represented as the correlation between the consumption by minke whale and fisheries catch through their shared resource, Atlantic cod. The correlation is positive.

Category	Species	Biomass	Inflow	Correlation [95% CI]
Prey	Cod	1899	149	
Predator 1	Minke whale	698	74	0.13 [-0.15, 0.41]
Predator 2	Demersal fisheries	0	619	

Table 29. The direct interaction represented as the correlation between the consumption by minke whale and fisheries catch through their shared resource, other demersal fish. The correlation is negative.

Category	Species	Biomass	Inflow	Correlation [95% CI]
Prey	Other demersal fish	2331	169	
Predator 1	Minke whale	698	160	-0.03 [-0.36, 0.31]
Predator 2	Demersal fisheries	0	335	

Table 30. The direct interaction represented as the correlation between the consumption by minke whale and fisheries catch through their shared resource, capelin. The correlation is positive.

Category	Species	Biomass	Inflow	Correlation [95% CI]
Prey	Capelin	2342	NaN	
Predator 1	Minke whale	698	476	0.24 [0.02, 0.44]
Predator 2	Pelagic fisheries	0	198	

8.7.1.2.3 Other baleen whales

Table 31. The direct interaction represented as the correlation between the consumption by other baleen whales and fisheries catch through their shared resource, capelin. The correlation is positive.

Category	Species	Biomass	Inflow	Correlation [95% CI]
Prey	Capelin	2342	NaN	
Predator 1	Other baleen whales	1331	830	0.43 [0.18, 0.66]
Predator 2	Pelagic fisheries	0	198	

8.7.1.2.4 Toothed whales

Table 32. The direct interaction represented as the correlation between the consumption by toothed whales and fisheries catch through their shared resource, Atlantic cod. The correlation is positive.

Category	Species	Biomass	Inflow	Correlation [95% CI]
Prey	Cod	1899	149	
Predator 1	Toothed whales	544	127	0.17 [-0.05, 0.41]
Predator 2	Demersal fisheries	0	619	

Table 33. The direct interaction represented as the correlation between the consumption by toothed whales and fisheries catch through their shared resource, other demersal fish. The correlation is negative.

Category	Species	Biomass	Inflow	Correlation [95% CI]
Prey	Other demersal fish	2331	169	
Predator 1	Toothed whales	544	511	-0.09 [-0.35, 0.18]
Predator 2	Demersal fisheries	0	335	

Table 34. The direct interaction represented as the correlation between the consumption by toothed whales and fisheries catch through their shared resource, capelin. The correlation is positive.

Category	Species	Biomass	Inflow	Correlation [95% CI]
Prey	Capelin	2342	NaN	
Predator 1	Toothed whales	544	367	0.33 [0.04, 0.60]
Predator 2	Pelagic fisheries	0	198	

8.7.1.2.5   Seals

Table 35. The direct interaction represented as the correlation between the consumption by seals and fisheries catch through their shared resource, Atlantic cod. The correlation is positive.

Category	Species	Biomass	Inflow	Correlation [95% CI]
Prey	Cod	1899	149	
Predator 1	Seals	260	102	0.16 [-0.09, 0.42]
Predator 2	Demersal fisheries	0	619	

Table 36. The direct interaction represented as the correlation between the consumption by seals and fisheries catch through their shared resource, other demersal fish. The correlation is negative.

Category	Species	Biomass	Inflow	Correlation [95% CI]
Prey	Other demersal fish	2331	169	
Predator 1	Seals	260	334	-0.23 [-0.48, 0.06]
Predator 2	Demersal fisheries	0	335	

Table 37. The direct interaction represented as the correlation between the consumption by seals and fisheries catch through their shared resource, capelin. The correlation is positive.

Category	Species	Biomass	Inflow	Correlation [95% CI]
Prey	Capelin	2342	NaN	
Predator 1	Seals	260	541	0.37 [0.13, 0.59]
Predator 2	Pelagic fisheries	0	198	

8.7.2   Food-web mediated interaction

Not all food-web mediated correlation coefficients are provided.

8.7.2.1   Marine mammals

Table 38. The correlation coefficient for krill in both seas between marine mammals and adult herring.

Category	Species	Biomass	Inflow	Correlation [95% CI]
Prey	Krill	0	NaN	
Predator 1	Minke whale, toothed whales, other baleen whales & seals	2029	2840	0.00 [-0.35, 0.34]
Predator 2	Adult herring	4577	3498	

Table 39. The correlation coefficient for krill in both seas between marine mammals and blue whiting.

Category	Species	Biomass	Inflow	Correlation [95% CI]
Prey	Krill	0	NaN	
Predator 1	Minke whale, toothed whales, other baleen whales & seals	2029	2840	0.05 [-0.30, 0.43]
Predator 2	Blue whiting	3606	3648	

Table 40. The correlation coefficient between consumption by marine mammals and demersal fish through their shared resource in the Barents Sea, capelin. The correlation is entirely positive, indicating that increased capelin biomass will increase both predator groups their consumption of capelin.

Category	Species	Biomass	Inflow	Correlation [95% CI]
Prey	Capelin	2342	NaN	
Predator 1	Minke whale, toothed whales, other baleen whales & seals	2833	2214	0.76 [0.63, 0.86]
Predator 2	Cod & other demersal fish	4230	2555	

Table 41. The correlation coefficient between marine mammals and demersal fish through their shared resource in the Barents Sea, juvenile herring. The correlation is entirely positive, indicating that increased juvenile herring biomass will increase both predator groups their consumption of capelin.

Category	Species	Biomass	Inflow	Correlation [95% CI]
Prey	Juvenile herring	2342	NaN	
Predator 1	Minke whale, toothed whales, other baleen whales & seals	2833	2214	0.35 [0.06, 0.60]
Predator 2	Cod & other demersal fish	4230	2555	

Table 42. The correlation coefficient for krill in both seas between marine mammals and all fish predating on krill. The correlation is negative with the 95% confidence interval crossing the zero. Indicating that the correlation is negative, however a positive correlation is not excludible as a plausible correlation.

Category	Species	Biomass	Inflow	Correlation [95% CI]
Prey	Krill	0	NaN	
Predator 1	Minke whale, toothed whales, other baleen whales & seals	2833	3213	-0.09 [-0.43, 0.26]
Predator 2	Herring, blue whiting, mackerel, cod, polar cod, capelin, juvenile herring & other demersal fish	21151	23727	

Table 43. The correlation coefficient between the consumption by marine mammals and all pelagic fish in the Norwegian Sea for Norwegian Sea resources outside the model domain. The correlation is positive with the 95% confidence interval crossing the zero. Indicating that the correlation is positive, however a negative correlation is not excludible as a plausible correlation.

Category	Species	Biomass	Inflow	Correlation [95% CI]
Prey	Zooplankton, krill & mesozooplankton and other fish in the Norwegian Sea	0	NaN	
Predator 1	Minke whale, toothed whales, other baleen whales & seals	2833	3847	0.07 [-0.29, 0.42]
Predator 2	Adult herring, blue whiting & mackerel	11750	6373	

Table 44. The correlation coefficient for Barents Sea resources outside the model domain between marine mammals and all pelagic fish in the Barents Sea. The correlation is negative with the 95% confidence interval crossing the zero. Indicating that the correlation is positive, however a negative correlation is not excludible as a plausible correlation, however unlikely as the 97.5% confidence interval is just above zero. Making this correlation almost exclusively negative, indicating a possible competition between the predators and this shared resource.

Category	Species	Biomass	Inflow	Correlation [95% CI]
Prey	Benthos, amphipods, copepods & krill in the Barents Sea	0	NaN	
Predator 1	Minke whale, toothed whales, other baleen whales & seals	2833	3273	-0.29 [-0.56, 0.03]

| Predator 2 | Cod, other demersal fish, capelin, polar cod & juvenile herring | 9401 | 16177 | |

Table 45. The correlation coefficient for Norwegian and Barents Sea resources outside the model domain between marine mammals and all fish in the Norwegian and Barents Sea. The correlation is completely negative with the 95% confidence interval not crossing the zero. Indicating that the interaction between the predators is competitive through this shared resource.

| Category	Species	Biomass	Inflow	Correlation [95% CI]
Prey	Benthos, amphipods, copepods & krill in the Barents Sea, Zooplankton, krill & mesozooplankton and other fish in the Norwegian Sea	0	NaN	
Predator 1	Minke whale, toothed whales, other baleen whales & seals	2833	3977	-0.37 [-0.63, -0.09]
Predator 2	Cod, other demersal fish, capelin, polar cod & juvenile herring, Adult herring, blue whiting & mackerel	21151	22550	

8.7.2.2 Toothed whales
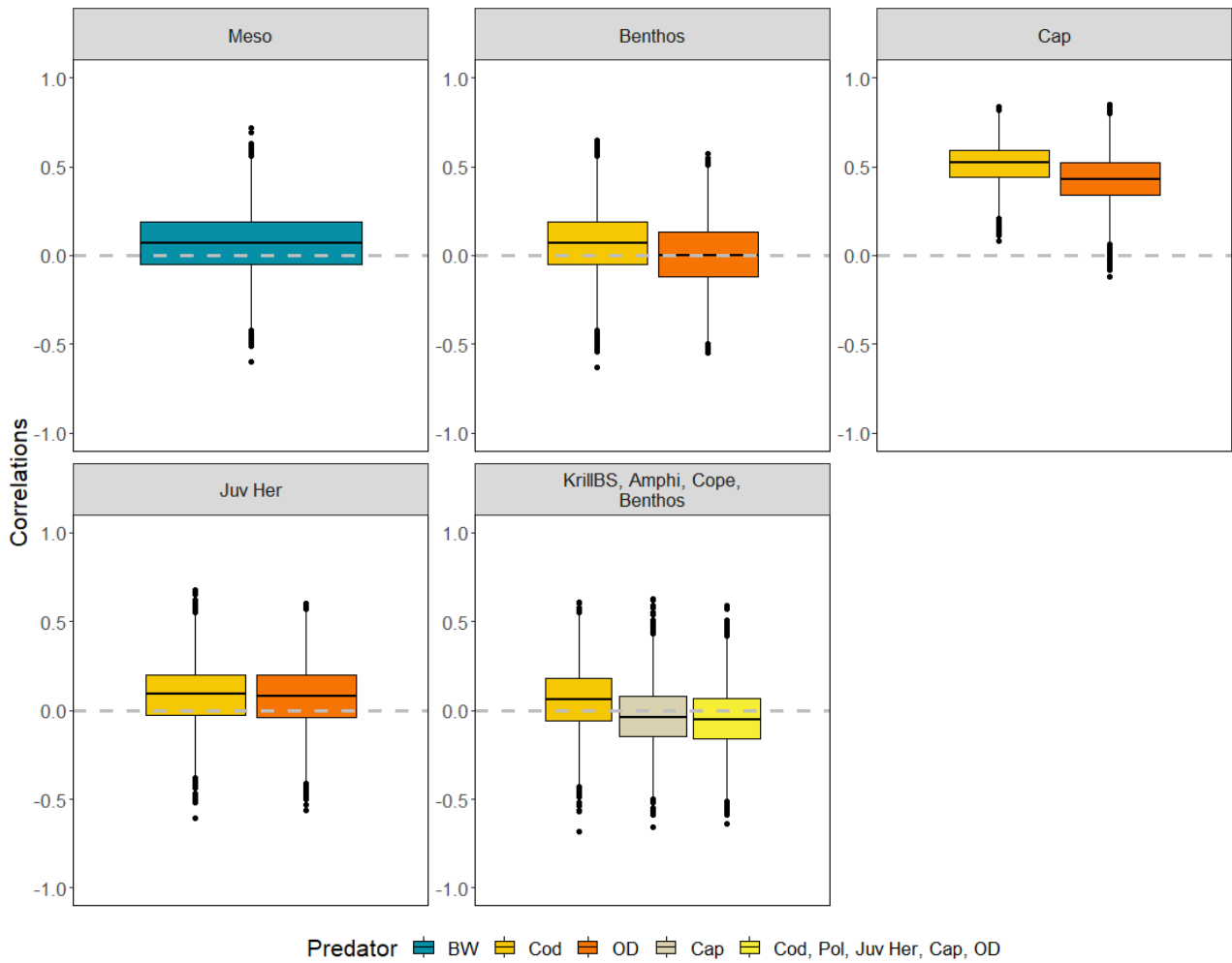
Figure 14, Distributions of the correlation coefficients between consumption by toothed whales and by other predators (groups) for different prey species. Each plot is a different prey (group) abbreviated following the List of abbreviations, with each boxplot in them representing different predators. They are represented as different colours and are abbreviated following the List of abbreviations. A positive correlation indicates an increase in the consumption of one prey species by marine mammals corresponds to a concurrent increase in consumption of the same species by the other predator. A negative correlation indicates with an increase in the consumption of the prey species by marine mammals corresponds to a concurrent decrease in consumption of the same species by the other predator, or vice-versa.
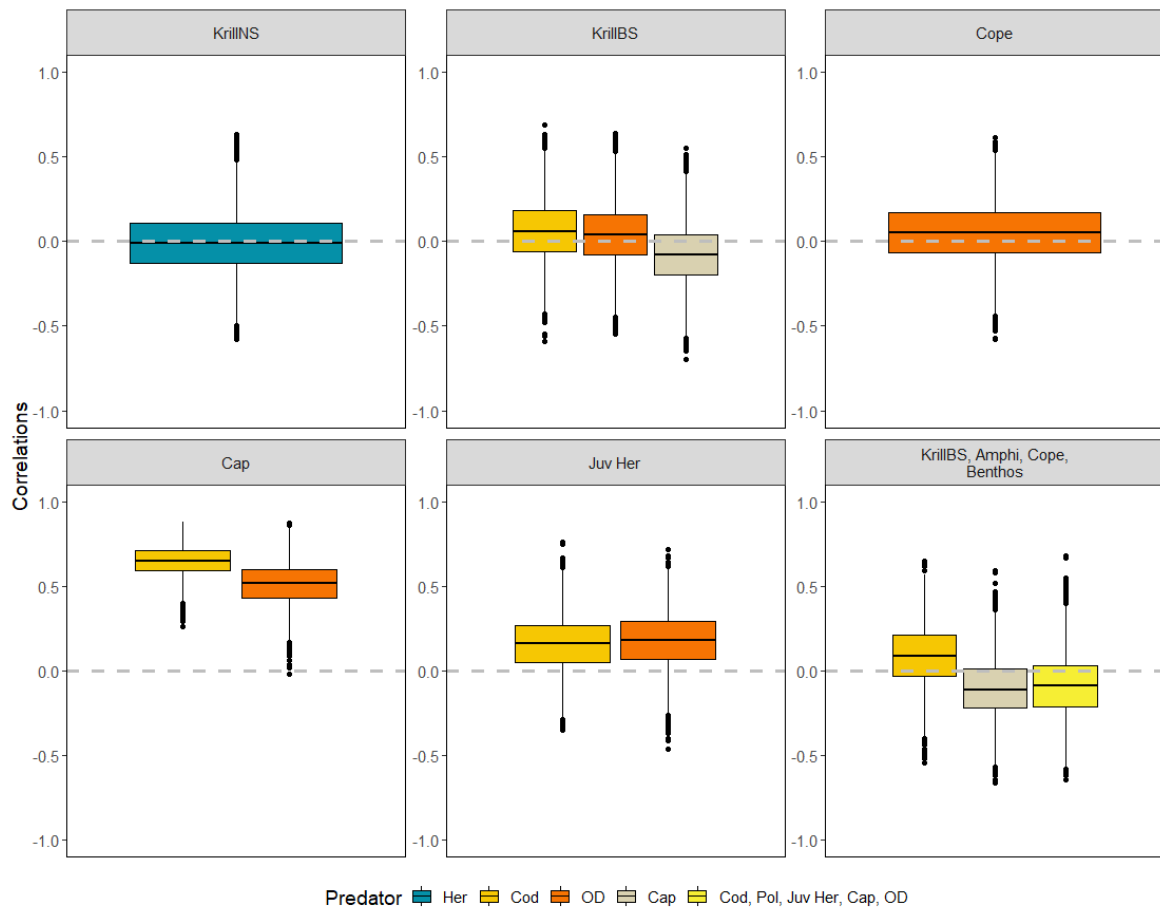
8.7.2.3   Other baleen whales

Figure 15, Distributions of the correlation coefficients between consumption by other baleen whales and by other predators (groups) for different prey species. Each plot displays a different prey (group) abbreviated following the List of abbreviations, with each boxplot in them representing different predators. They are represented as different colours and are abbreviated following the List of abbreviations. A positive correlation indicates an increase in the consumption of one prey species by marine mammals corresponds to a concurrent increase in consumption of the same species by the other predator. A negative correlation indicates with an increase in the consumption of the prey species by marine mammals corresponds to a concurrent decrease in consumption of the same species by the other predator, or vice-versa.
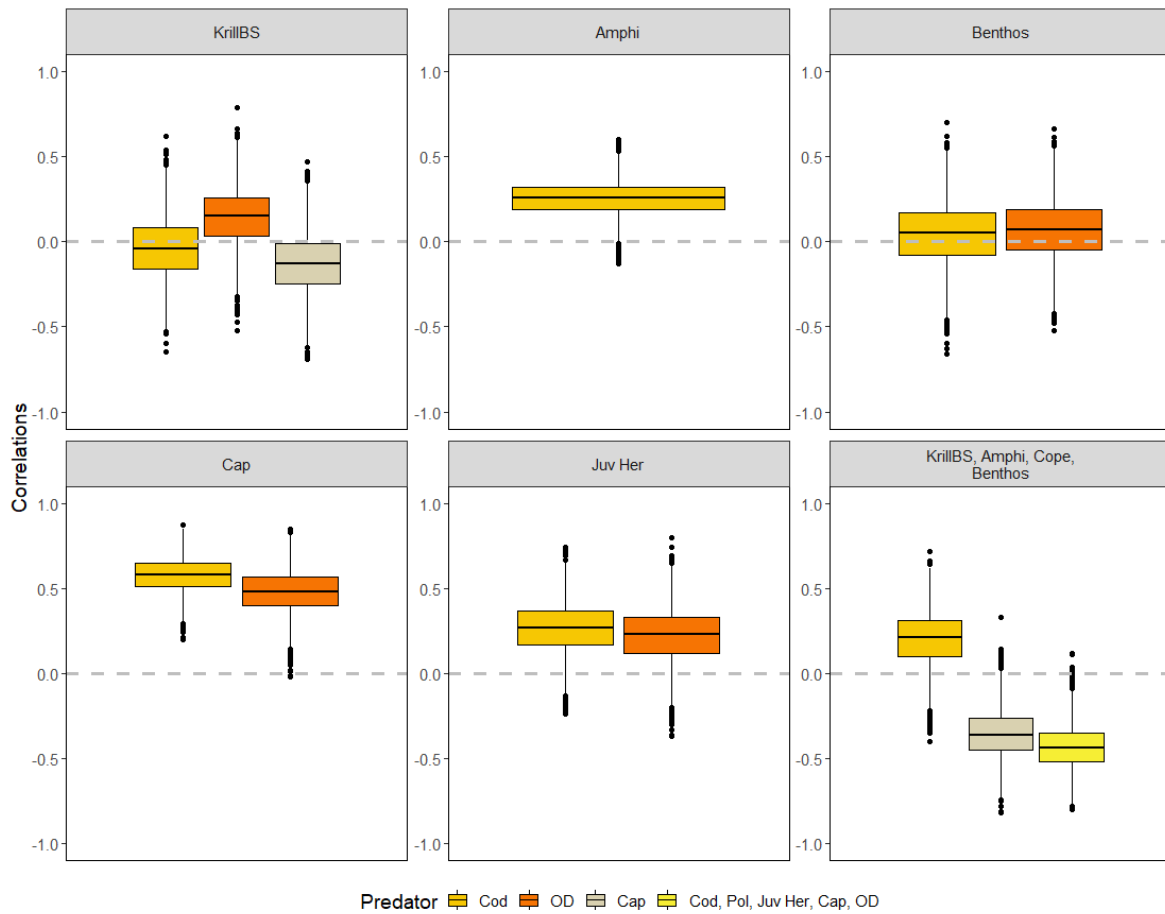
8.7.2.4   Seals

Figure 16, Distributions of the correlation coefficients between consumption by seals and by other predators (groups) for different prey species. Each plot displays a different prey (group) abbreviated following the List of abbreviations, with each boxplot in them representing different predators. They are represented as different colours and are abbreviated following the List of abbreviations. A positive correlation indicates an increase in the consumption of one prey species by marine mammals corresponds to a concurrent increase in consumption of the same species by the other predator. A negative correlation indicates with an increase in the consumption of the prey species by marine mammals corresponds to a concurrent decrease in consumption of the same species by the other predator, or vice-versa.

8.8 Appendix 8 – Objectives, Patterns and Evaluation

Name of the study:

Food web-mediated interaction between marine mammals and fisheries in the Norwegian and Barents seas.

Author(s): Lucas Bas

Date: 11.05.2023

DOI (if applicable):

Repository (e.g. GitHub): https://github.com/LucasBas14/RCaN-Marine-Mammals-github

Prior model developments and historical context:

(Planque, Favreau, et al., 2022)

8.8.1 Objectives

8.8.1.1 Context and motivations

1. What are the objectives of the model application

The Norwegian and Barents Seas are productive marine ecosystems that support diverse fish stocks that utilise these waters as their spawning and feeding grounds. Some notable species that play a central role within the ecosystem are Atlantic herring (Clupea harengus)*, blue whiting* (Micromesistius poutassou)*, Atlantic mackerel* (Scomber scombrus)*, capelin (*Mallotus villosus*), and Atlantic cod* (Gadus morhua)*. These species additionally are major contributors to the fishing industry and have been fished for a few decades. These fish stocks have been monitored over the past few decades and are in a range of biomass of at least 2 MT each and some have reached 8 MT. These fish stocks have two extractors, marine mammals, and the fisheries industry. In the past, marine mammals were culled to achieve a potentially higher fisheries harvest, but the result of a recent paper by Skern-Mauritzen et al., 2022, shows that they are operating on different trophic levels and therefore a direct competitive interaction is unlikely.*
The marine mammals however have a total annual consumption that is almost 5 times higher than that of fisheries, 11.7 MT and ca. 2.61 MT, respectively. That makes it so that marine mammals play a significant role in determining the energy flow through the food web in these regions and have done so in the past. The fisheries target species with high food-web connectivity that could make the marine mammal-fisheries interaction more complicated as it may be present as a food web mediated connection. To better understand these food web mediated effects models are needed to investigate mammal-fisheries' direct and indirect interaction over the past few decades.

The objective is to analyse whether the biomass of marine mammals in the Norwegian and Barents Seas was affected by changes in prey biomass driven by fisheries catch and vice versa over the past decades.

2. Why is the model suitable to address the objectives?

The CaN model is a data-driven modelling approach that constraints trajectories based on data entries and parameterization. This allows the ecosystem to be constrained by the data provided, and all the possible trajectories can be projected from the past decades. The outputs of the models are reconstructions of the time series of species biomass and all fluxes. These outputs are appropriate to evaluate the possible existence of trophic controls relating consumption or predation (fluxes) to population dynamics (variation in biomass). These model trajectories can be explored and examined for the direct and indirect effects of the fisheries on the biomass of marine mammals through the food web and vice versa.

3. What would count as successful in achieving these objectives?

Successful would be when the model produces an output that corresponds and aligns with expert knowledge and independent data of the ecosystem and its dynamics over the past decades.
To check the model outputs there are sanity checks , which are ways of identifying if the model behaves as intended and resembles the input data, given the input data is correct.
As an output there are possible emerging patterns and if these patterns are meaningful, that means the model is successful.

8.8.2   Specific model setup

4. Are there any deviations from the original model description?

    a. In the model assumptions?

    b. In the model structure – submodels, variables, components, scales?

    c. In the model details – parameter values, functional relationships

    d. In the model forcing – initial conditions, boundary conditions, observation forcing, maps?

This modelling approach is taken from (Planque, Favreau, et al., 2022) and modified to fit the current study. Modifications are:

- *Species composition, as the model area and question are different.*

    o *Moved components from inside to outside model domain:*

        ▪ *Copepods → zooplankton (Norwegian Sea)*

        ▪ *Krill → Krill (Norwegian Sea)*

        ▪ *Amphipods → zooplankton (Norwegian Sea)*

    o *Added components inside model domain:*

        ▪ *Minke whale*

        ▪ *Other baleen whales*

        ▪ *Toothed whales*

        ▪ *Seals*

        ▪ *Cod*

- Polar cod

- Other demersal fish

- Juvenile herring

- Capelin

  o Added components outside model domain:

  - Demersal fisheries

  - Minke whale fisheries

  - Seal fisheries

  - Krill (Barents Sea)

  - Amphipods (Barents Sea)

  - Copepods (Barents Sea)

  - Benthic fauna (Barents Sea)

- Parameter values, with the change in components this also applies to the parameters. Different species are represented, and their specific parameters are applied.

8.8.3   Patterns

8.8.3.1   Selected patterns

5. Which ecological patterns are used for the model evaluation?

   a. temporal patterns such as cycles, regime shift or trends, measures of temporal variability, and autocorrelation.

   b. spatial patterns such as spatial synchrony, traveling waves, patchiness, and autocorrelation.

   c. structural and functional patterns, such as taxonomic diversity, biomass ratios, integrated production, diet fractions, and trait distributions.

   d. Other relevant patterns

Multiple ecological patterns are used to evaluate the model output. The predominant pattern for the model evaluation is the collection of time series of fluxes between our components and the biomass. This is a temporal pattern. With the model being data-driven, it is so that there is

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no possibility to compare the model outputs to the known data, as this is used to constrain the model. However, the model output can be evaluated and matched to the provided data. This can be done by checking all the trajectories for leaning against a boundary or operating in a smaller band within the constraints. If this is the case, it means that the model can only create a polytope that is bounded and can be sampled if this parameter is within a very specific range. Thus, implying that other constraints are forcing the output in this narrow band or against a boundary.

Another ecological pattern, a functional pattern, that will be used is the 'production over biomass' (P/B) in relation to fishing catches.
More specifically, it is the width of the distribution of the correlation coefficients (see question 5) that can serve as a measure of success (wide distribution ≈ the model is not informative, narrow distribution ≈ the model outputs tell something about the trophic interactions). This tells about the correlation between the biomass of marine mammals and their correlating pelagic fishing industry catch amount. By investigating this dynamic, it is possible to identify a food web-mediated effect between marine mammals and fisheries

6. Why are these patterns important/essential to address the objectives?

The temporal patterns in biomass and fluxes are essential to address the objective of identifying whether the biomass of marine mammals in the Norwegian and Barents Seas was affected by an alteration in prey availability generated by the catch of the pelagic fishing industry over the past decades. They project the temporal change of the biomass that is needed to address this objective
It is assumed that if the reconstruction of variations in biomass and fluxes are robust to model structure, parameters, and data uncertainty, then the derived patterns of growth, consumption, and predation are also considered robust.

Other patterns include consumption correlation patterns. This correlation defines a negative or positive correlation between two predator(s) (groups) in relation to a selected prey (group). This can be used to assess whether the interactions between the predators are competitive or if they are both optimistic predators when the prey biomass increases.

8.8.4 Independent data

7. Where do the independent data originate from?

Most of the data is originating from the ICES reports that provide species- and region-specific stock assessments and surveys, catch data, and weight-at-age data. Other sources of independent data are gathered from previously constructed models and other published literature on the species used in the present study.
The full model description with all the data series and data to constrain the model are not provided. They could be acquired in the form of an xlsx file.

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8. What are the extent and resolution of the independent data?

The resolution of most of the data is annual, with some data that is constant throughout the model or through certain time ranges.

9. How representative of the ecological processes are the independent data?

The data that is used is annual data available from surveys and other model outputs. This is representative of the data needed for this modelling approach to explore the objectives. The objectives are on an interannual temporal spectrum, and this makes the annual data a sufficient way of providing information.

10. Are there estimates of independent data accuracy, precision, bias, or uncertainty?

Most of the independent data has presented itself with confidence intervals which are then used as upper and lower boundaries. For data that is presented as a single measure an upper and lower boundary is created by adding and subtracting 20% of that measure and thus using 0.8 and 1.2 times the initial value as boundaries.

Another way of dealing with uncertainty, precision, accuracy, and bias is done by the model itself. The model is data-driven and thus will become more accurate the more information is fed into it. This happens because the ecosystem is connected all the way through, therefor a constraint on one component will constrain the next components in line.

11. How are the independent data processed to represent the selected patterns? Are assumptions made to derive these patterns from the data?

The independent data is processed from annual biomass data and diet fractions to derived information. This includes the biomass growth, consumption, and diet summary. This is realised by simulating the model with the constraints in place over the past few decades. The output will be all the possible trajectories possible given the constraints. Which can then be used to derive the previously mentioned information to represent the selected patterns.

8.8.5   Model outputs

12. Which model outputs are used for the evaluation?

For the evaluation of the model the following model outputs are used:

- *The time-series, to check if the output follows the data.*

- *The fluxes, to check if the consumption by each predator on each prey is accurate to data/ expert knowledge.*

Therefor all the initial outputs are used in the model evaluation.

13. Have the outputs been post-processed, and how?

*The initial outputs from the model are the biomass trajectories and the time-series of fluxes, all other outputs are derived from these. The steps of postprocessing are detailed in the **Materials and methods** section of the main thesis. These include derivation of diet composition, consumption (total, per prey, or per unit biomass of the predator), predation (total, per predator, or per unit biomass of the prey), and consumption correlation.*

14. Are there estimates of model output accuracy, precision, bias, or uncertainty?

The CaN model outputs are different from outputs from Ecopath with Ecosim. This is because there is no one most likely outcome/time-series. Rather, the CaN model outputs provide a large collection of possible food-web dynamics that reflect the ecosystem and its constraints. All the trajectories together reflect the uncertainty in the food-web dynamics. The wider spread the trajectories the more uncertain and vice versa with the smaller spread, less uncertain.

15. Are additional assumptions made when deriving patterns from model outputs?

No.

8.8.6   Evaluation

8.8.6.1   Evaluation methodology

16. Are sanity checks conducted? If so, what is the method used? If not, explain why.

    a. Which data and patterns are used for this?

    b. Does this apply to patterns that are not otherwise evaluated for this model application?

Sanity checks are used along the way for checking the model outputs for unrealistic pattern. The sanity checks include:

- *The mean/distribution of the biomass for each trophospecies visually looks ok.*

- *The mean/distribution of the catches for each fishery visually looks ok.*

- *Plots of the cumulated time series of catches visually looks ok.*

- *Plots of the cumulated time-series of biomass visually looks ok.*

- *The diet matrix (diet proportions for each predator) visually looks ok.*

- *The time series for the biomass of the major commercial fish species resemble the input data.*

- *The time series for the catches of the major commercial fish species resemble the input data.*

- *The sampling chains look non-autocorrelated.*

- *The time series for all biomass and fluxes are well "distributed", i.e. not clogged towards a upper or lower limit.*

17. What is the methodology used to compare ecological patterns derived from independent data with patterns from the model?

    a. What is the rationale for choosing this method?

    b. How are observational and/or model output uncertainties handled?

    c. Does the methodology rely on specific assumptions?

    d. Were other methods experimented? If they didn't succeed, explain why.

This method of modelling is used as it does not need data to be assessed afterwards, but it uses data in the building process and therefore should always adhere to this data. This is under the condition that the combination of all data can produce a working dynamic. Hence, the first step of the model evaluation is to check that the model can be built into a working polytope, working dynamics. Afterwards, the model is sampled, and sanity checks are performed.
This modelling approach is chosen as it directly tries to fit observational data into the dynamics of the model in the form of constraints. These constraints are also the way the model deals with uncertainties. These constraints can be placed on data with the uncertainty included in the information. Say, we have a mean total consumption of minke whales and a 95% confidence interval. Three constraints can be made:

- *Mean consumption over time is equal to the reported mean.*

- *The upper limit of consumption is at most the upper limit of the 95% CI.*

- *The lower limit of consumption is at least the lower limit of the 95% CI.*

The output uncertainty is presented as the collection of possible food-web dynamics that reflect the ecosystem and its constraints. All the trajectories together reflect the uncertainty in the food-web dynamics. The wider spread the trajectories the more uncertain and vice versa with the smaller spread, less uncertain.

There are no other assumptions besides the assumption in question 9.

No other methods were experimented before coming to the CaN modelling approach.

18. Is there a threshold level (match between observed and modelled patterns) that can separate acceptable from unacceptable models?

The model is deemed unacceptable when the sanity checks are not passed. Essential patterns for answering the objective are correlation patterns, diets, and consumption. The broader the uncertainty surrounding these patterns, the less certain the model conclusion becomes.

19. How comparable are the patterns derived from the model and those derived from the independent data?

They are comparable. No comparability measures were used; however, the patterns were discussed with experts.

8.8.7 Sensitivities

20. Has a model sensitivity analysis been performed? If so, how? If not, explain why.

    a. on the model structure?

    b. on the model parametrization?

    c. on other aspects of the model?

The analysis could be done on the implicit species-specific parameters of the trophospecies. By modifying them to the upper and lower limit, based on literature and uncertainties. However, because of limiting time this was not performed

21. Which elements are the modelled patterns most sensitive to?

    a. input parameters

    b. priors and assumptions

    c. structural elements

    d. processes

Not performed

22. How sensitive are the modelled patterns to the choice of initial conditions, boundary conditions, spatial and temporal resolution?

Not performed

23. How sensitive is the model evaluation to the independent data availability and uncertainty?

The model is data driven and thus is not sensitive to data availability nor uncertainty as these are implemented within the constraints of the model.

24. How much is the model evaluation constrained by computational or theoretical limits?

The model is in comparison to Ecopath models relatively simple. However, with each increase of a component, flux, or constraint the model complexity increases exponentially. The sampling of the model is in the range of a couple of hours dependent on the number of trajectories.

25. How does the perceived performance of the model depend on the chosen evaluation methodology?

No other modelling approach was tested/used to evaluate the performance of the present model.