

Exploring balanced harvesting by using an Atlantis ecosystem model for the Nordic and Barents Seas



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By

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Front cover photo: Beautiful afternoon aboard Kristine Bonnevie (Sognefjorden, Norway)

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Abstract

To meet the objectives of the Ecosystem Approach to Fisheries, “Balanced Harvesting” (BH) has been suggested as a possible strategy to ensure a high sustainable yield while maintaining ecosystem structure and function. BH proposes a moderate fishing mortality in proportion to productivity spread across the widest possible range of species, stocks, and sizes in an ecosystem. The intent is a sustainable and overall unselective harvest that reduces alterations to the ecosystem structure by maintaining the relative size and species composition, while increasing total yield.

The Norwegian and Barents Seas have been subjected to moderate fishing pressure and elements of an ecosystem-based approach to management for many years. By using a pre-parameterized Atlantis ecosystem model of the Nordic and Barents Seas, we investigated the ecosystem effects of a BH regime. This was done by running simulations with combinations of historic fishing pressure and fishing mortality rates proportional to 25% of the productivity of selected species. The simulations were then compared to a control run where the historical fisheries were applied.

The model results imply that implementing a BH regime in the Norwegian and Barents Seas would only produce marginal increases in total yields of commercially exploited stocks, possibly because the Norwegian fisheries already is fairly balanced. The inclusion of non-commercial species in the harvest, on both lower and higher trophic levels, caused unexpectedly drastic changes to the ecosystem in the form of stock collapses or severely changed biomass levels. This study represents the first attempted examination of implementing balanced harvesting based on productivity, using an Atlantis ecosystem model.

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1. Introduction

With a rapidly growing human population, likely approaching 9 billion by 2050 (United Nations, 2017), the need for food is one of the greatest challenges the world is facing. The United Nations Sustainable Development Goals (SDGs) addresses in SDG2 the zero-hunger goal and in SDG14 conserving and sustainable use of life below water, as two of the 17 most important issues in the world (United Nations, 2015). Today, only 2 % of the food is harvested from the oceans, yet half of the world’s primary production is marine (Field *et al.*, 1998). The demand for nutrients and protein has never been more important and expanding the exploitation of the ocean would seem like a good way to go.

Still, fisheries today are generally considered to be in a scarce condition with little room for further expansion. According to the FAO statistics, 90 % of the fished stocks are already either fully exploited (61%) or beyond sustainable limits (29%) (FAO, 2014). Some have even proclaimed that there will be nothing left to fish within the next 50 years, if current trends continue (Black, 2006). The ocean’s potential to meet the future demand of a growing human population has therefore been questioned.

When comparing human food potential, it is important to take into consideration that the aquatic food chain is fundamentally different from the terrestrial. While the terrestrial vegetation is dominated by large vascular plants, most marine primary producers are microscopic algae.

This affects the size pattern of the aquatic and terrestrial herbivores. Land-based food webs have generally larger organisms at low trophic levels and are thereby often shorter and much more efficient in terms of providing food for humans. Around 90 % of the energy in the food chain is lost at every trophic level, which makes high levels much less energy efficient compared to low. The harvest pattern from the oceans is on average 2 trophic levels higher, i.e. on “lion-eaters” compared to a land-based system (Figure 1.1) (Kolding *et al.*, 2016).

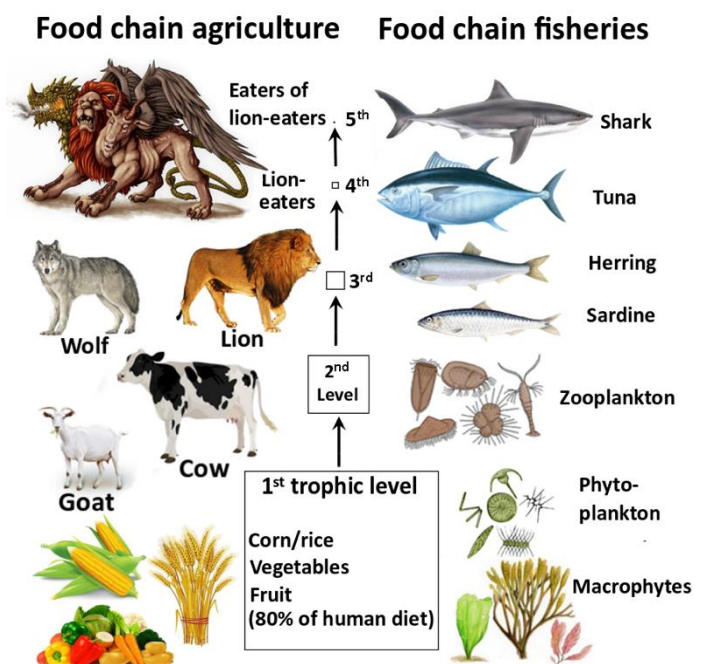


Figure 1.1 Comparison of terrestrial and aquatic food chain (Modified from Kolding *et al.*, 2016).

1.1 EAF and EBFM

Fisheries have obvious impacts on the oceans, which are expected to increase in line with an increasing human population and a greater demand for food. The main objective of modern fisheries management is to develop strategies that ensure efficient and maximum sustainable utilization of marine production (UNCLOS, 1982), while preserving the structure and functioning of harvested stocks and ecosystem (CBD, 1992).

The concept of Ecosystem Approach to Fisheries (EAF) has been proposed as a holistic framework to deal with this objective, and have become a goal in fisheries management (Kolding *et al.*, 2016). EAF was defined by the 1998 Malawi Principles (UNEP/CBD, 1998), and adopted formally by the Convention on Biological Diversity in 2000 (CBD Decision V/6). Principle 5 explicitly refers to EAF by stating that “*conservation of ecosystem structure and functioning, in order to maintain ecosystem services, should be a priority target of the ecosystem approach*”. This is based on the assumptions that ecosystem services are essential for the well-being of humans and other species who all depend on these services for survival, and that in order to continue provision of these services, maintaining the ecosystem function and structure is required. In the years since these principles were established, scientific evidence has increasingly reinforced these assumptions (Garcia *et al.*, 2015).

Norway has committed to implement an Ecosystem-Based Fisheries Management (EBFM) in the North Sea, Norwegian Sea, and Barents Sea (Olsen *et al.*, 2007; Miljøverndepartementet, 2006; 2009; 2011). According to Pitcher *et al.* (2009), implementing an ecosystem-based management in Norway should be relatively straightforward as it scores high on ecosystem-based principles already, according to the code of conduct of responsible fisheries (FAO, 1995). Although largely regulated by conventional single species management, there are several ecosystem considerations in the Norwegian fishery. One example is the management of Northeast Arctic cod and Barents Sea capelin where the importance of capelin as food for cod has been considered in the capelin fishery since 1991 (ICES, 2015a). However, as in other countries it is still unclear exactly how an implementation of EBFM should be done, specifically how to find the balance between “exploiting” and “protecting” (Howell *et al.*, 2016).

1.2 Balanced harvesting

To meet the objective of the Ecosystem Approach to Fisheries, “Balanced Harvesting” (hereafter BH) has been suggested as one possible strategy to ensure a high sustainable yield while maintaining ecosystem structure and function. Garcia *et al.* (2012) defined BH as “*a moderate fishing pressure across the widest possible range of species, stocks, and sizes of an ecosystem, in proportion to their natural productivity so that the relative size and species composition is maintained*”.

BH can be considered as a systematic attempt to take fisheries management to the ecosystem level (Law *et al.*, 2016). This is to be achieved through exposing all components of the ecosystem, from zooplankton to top predators, to a fishing mortality proportional to their size-specific productivity. The idea has attracted broad interest worldwide and has been supported by both empirical studies in African lake ecosystems with small-scale fisheries (Kolding and van Zwieten, 2014; Kolding *et al.*, 2015) and by modelling studies of marine systems (Garcia *et al.*, 2012; Law *et al.*, 2013). These studies suggest that a balanced harvest may increase the total sustainable yield, while maintaining ecosystem structure, compared to today’s selective harvesting.

The BH concept emerged from a widespread concern of the problems caused by conventional selective fishing management resulting in decrease in global catches (FAO, 2016), overfishing of target species (Costello *et al.*, 2012; Sumaila *et al.*, 2012), depletion of large predatory fish (Christensen *et al.*, 2014), and age-truncation and potential fisheries-induced evolution (Heino & Godø, 2002; Hsieh *et al.*, 2010; Law, 2007).

Fisheries are conventionally highly selective with the aim of targeting specific species and size groups while protecting others. Selectivity is deeply engrained in our fishery historically, where fishermen have always targeted the largest individuals and species, while protecting young and juveniles for economic and ethical reasons (Kolding *et al.*, 2015). This fishing mortality has the opposite pattern of the natural predation mortality (Figure 1.2).

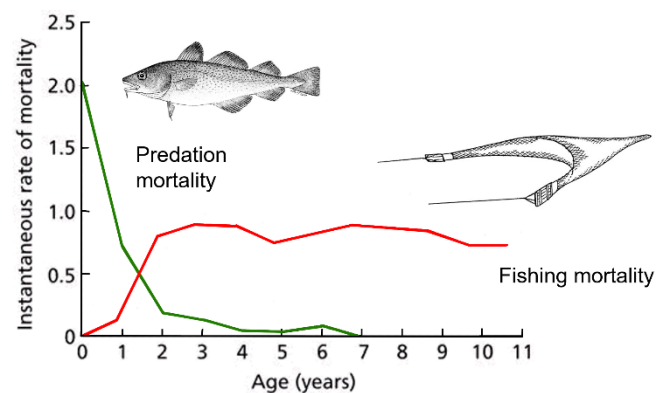


Figure 1.2 Fishing mortality (red line) increases with age, while the predation mortality (green line) decreases with age it reduces the chance of being eaten (Modified from Kolding & van Zwieten, 2011)

Any kind of selective removal will inevitably alter the composition of a population and consequently the structure and biodiversity of the ecosystem – even at moderate fishing levels (Garcia *et al.*, 2012). As marine trophodynamics are linked to size rather than taxonomy, changing of size spectra may alter the trophic structure and have various cascading effects on the community dynamics. There is increasing empirical evidence that systematic removal of large mature adults may cause both phenotypic and genetic shifts in populations in ways that could be difficult to reverse (Ricker, 1981; Jørgensen, 1990; Swain *et al.*, 2007; Trippel *et al.*, 1997). Deliberately targeting big fish and protecting young, may actually cause a so-called fisheries-induced evolution that favours early maturation and faster individual growth, resulting in smaller and smaller fish (Jørgensen *et al.*, 2007).

According to (Hixon *et al.*, 2014), there are additional problems with targeting the bigger fish, more specifically big, old, fat, fecund female fish (BOFFFFs). They summarised 4 benefits of conserving BOFFFFs (Figure 1.3):

1. Fecundity normally increase with age and body size since larger body allows development of larger ovaries, which then again produce more eggs.
2. Large females often produce larger and better provisioned eggs which results in larvae that have better chances of survival.
3. BOFFFFs in batch-spawning species tend to spawn more batches, have earlier and longer spawning seasons and may spawn in more favourable locations.
4. BOFFFFs can outlive periods when successful reproduction is hard and be ready to spawn profusely and enhance recruitment when favourable conditions return.

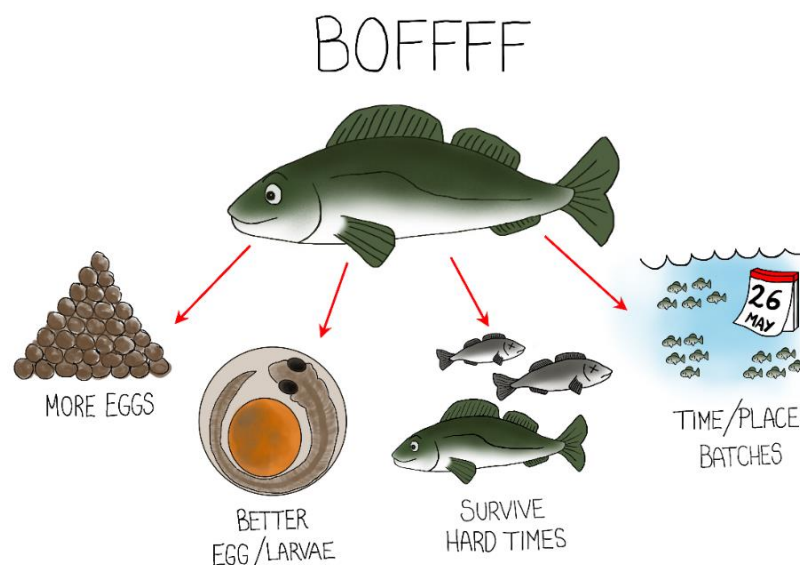


Figure 1.3 Benefits of conserving big, old, fat, fecund, female fish (BOFFFFs)

Populations with old-growth age structure and high abundance of BOFFFFs has shown to be more stable, more predictable, and less prone to overfishing collapse than age-truncated stocks. The fact that fishing generally causes declines in BOFFFFs abundance, could thereby also harm the fishery by reducing stock productivity and stability resulting in low/variable catches.

Fisheries-induced evolution is driven by selectivity as well as by its effect on overall mortality. If BH results in mimicking the natural mortality with predation-like fishing mortality, the evolutionary selection on life-history traits would be expected to be greatly reduced. And if an implementation of BH results in a more diverse fishing fleet with a wider range of fishing gears, then the risk of selection on any behaviour is reduced, in contrast to what happens in a fishery dominated by just a few gears such as trawl on the bottom and purse-seine in the water body (Zhou *et al.*, 2018).

However, it should be emphasised that BH does not call for an unselective and indiscriminate fishing. It is a common misconception that under BH, all fisheries are allowed to operate unselectively with a free-for-all-policy. In fact it has been argued that BH fishing may actually require a higher level of selectivity (Reid *et al.*, 2015). BH simply suggests a different type of selectivity at ecosystem level where the overall fishing pressure is spread over different species and body sizes in line with productivity in order to maintain ecosystem structure (Garcia *et al.*, 2015).

Still, the theory of balanced harvesting remains controversial (Froese *et al.*, 2016a; Froese *et al.*, 2016b; Pauly *et al.*, 2016), and is by some thought to be impossible to carry out in its pure theoretical form (Howell *et al.*, 2016). When comparing the global overall exploitation of the trophic levels (TL) with the production rate, there is little doubt that current fisheries are far from balanced (Figure 1.4). As productivity tend to decrease as a function of body size (Peters, 1986), moving towards BH would imply a reduced harvest of large fish and increased fishing on smaller species and individuals that are generally considered low-

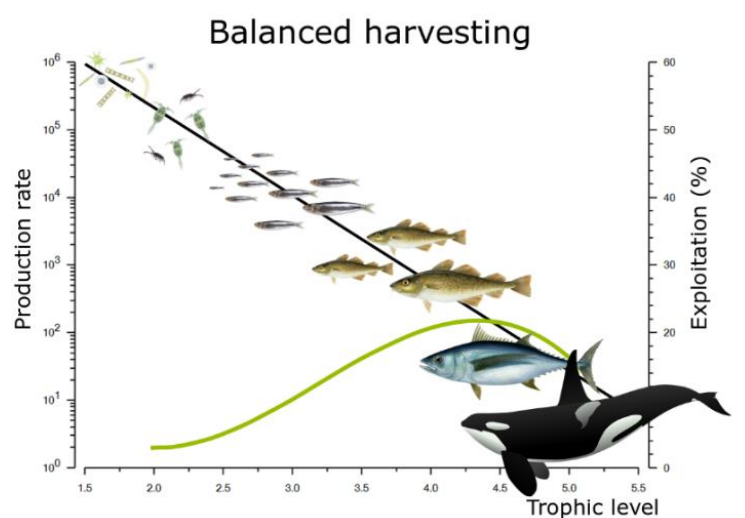


Figure 1.4 Comparison of conventional fishing pressure (green line) on trophic levels compared to production rate (black line) shows a peak at TL 4-5 (Modified from Kolding *et al.*, 2016)

value and unusable in the Western world. Even though balanced fishing has the potential to achieve an EBFM, and has been shown to be effective in giving a high yields with low impacts to the ecosystem size spectra in African small-scale fisheries, it is not clear that these results translate to large-scale modern fisheries (Howell *et al.*, 2016).

1.3 The Norwegian Sea and the Barents Sea

Throughout history the seas surrounding Norway have provided an abundant supply of fish as a nutritious and high-quality source of food. Even though it is a small country in terms of people, Norway has one of the longest coastlines in the world managing ocean areas of 2,3 mill km².

The Norwegian Sea is a part of the North Atlantic Sea located between Norway, Iceland and Svalbard (Figure 1.5). With an area of 1,1 million km² and an average depth of about 2000 m it comprises a volume of more than 2 million km³. The Norwegian Sea is divided into two separate basins of 3000-4000 meters depth, with maximum depth of 4020 m. Along the Norwegian coast there is a relatively narrow continental shelf of 40-200 km with varying topography and geology (ICES, 2008).



Figure 1.5. Map of the Norwegian and Barents Seas (https://en.wikipedia.org/wiki/Barents_Sea/media/File:Barents_Sea_map.png, 2018)

The ecosystem in the Norwegian Sea has a relatively low biodiversity, but the food chain is productive and certain species occur in very large numbers. The phytoplankton establishes the bottom of the food chain and is found in enormous quantities during the short, but intense spring blooms. Zooplankton species, like *Calanus finmarchicus*, is consumed by abundant fish stocks and a variety of marine mammals including minke whales as well as larger whales such as humpback and fin whales (Gjørseter *et al.*, 2009).

The fish community is characterised by large stocks of medium sized pelagic species such as Norwegian spring spawning herring (*Clupea harengus*), mackerel (*Scomber scombrus*) and blue whiting (*Micromesistius poutassou*). These stocks are highly migratory and none of them spend their entire life cycle within the Norwegian Sea. Both blue whiting and mackerel spawns west of the British Isles and the North Sea, before migrating back into the Norwegian Sea. Norwegian spring spawning herring, on the other hand, has its main spawning and feeding areas in the Norwegian Sea, but the main nursery area is in the Barents Sea. Vertically, mackerel is the one closest to the surface, herring is somewhat deeper, while the blue whiting has the deepest distribution (ICES, 2008).

Other abundant species include mesopelagic fish like pearlside (*Maurolicus muelleri*) and lanternfish (*Benthoosema glaciale*). These mesopelagic fish have a diel vertical migration and are important as food for several commercial species (ICES, 2008).

The circulation in the Norwegian Sea is strongly affected by the topography. From the west flows the cold, low salinity Arctic Water, while the warm, high salinity Norwegian Atlantic slope Current flows in from the south between Shetland and Iceland (Mork & Skagseth, 2010). Along the Norwegian coast and the continental shelf, flows the low salinity Norwegian Coastal Current.

The Barents Sea is a shelf sea of approximately 1.4 million km² located north of Norway and Russia. It is separated from the Norwegian Sea by the continental slope between Norway and Svalbard. Despite being the deepest of the Arctic Shelf Seas, it has a relatively shallow average depth of 230 m, although deeper channels and basins of 500 m exist (Sakshaug *et al.*, 2009).

The ecosystem is surprisingly diverse considering its northern distribution. The main commercial stocks are the Northeast Arctic cod (*Gadus morhua*), haddock (*Melanogrammus aeglefinus*), saithe (*Pollachius virens*) and capelin (*Mallotus villosus*). Capelin plays a major role in the ecosystem as one of the most important prey species in the Barents Sea. During the summer the stock migrates north and feeds on the zooplankton production near the ice edge before heading back south, serving as a major transporter of energy throughout the higher trophic levels (ICES, 2008).

The Barents Sea holds by far the largest cod stock in the world, and cod is considered the most important predator in the area feeding on a variety of prey. Beaked redfish (*Sebastes mentella*) and golden redfish (*Sebastes norvegicus*) are slow-growing, deep-water species that have been

heavily fished, and their fishing is now strictly regulated to rebuild the stocks. Greenland halibut (*Reinhardtius hippoglossoides*) is found around the eastern shelf and is also commercially exploited. Red king crab (*Paralithodes camtschatica*) was introduced to the Barents Sea in the 1960s (Jørgensen & Hop, 2005), while snow crab (*Chionoecetes opilio*), which is a true invasive species, has gradually increased its abundance in the later years. Northern shrimp (*Pandalus borealis*) is an important prey for several fish species, as well as commercially harvested (ICES, 2008). Species abundance is strongly influenced by both ocean climate and production (i.e. bottom-up regulation) and by predation (i.e. top-down regulation) (Johannesen *et al.*, 2012).

1.4 The Norwegian fishery

The Norwegian and Barents Seas are arguably some of the world's best monitored and managed fisheries (Kolding *et al.*, 2016). Norway possess the exclusive economic zones of some of the richest fishing grounds in the world, and fisheries have always been a central part of Norwegian culture and industry,

The Norwegian fishery targets a range of different species and size classes, and reflects overall, at the species level, a system that is harvested in a more balanced way than most marine systems (Howell *et al.*, 2016). Several trophic levels are harvested., including lower level species like the copepod *Calanus finmarchicus* (www.calanus.no) and higher level species like bird eggs, seals and whales.

Russia and Norway are the only countries that have exclusive economic zones in the Barents Sea, with Knipovich Polar Research Institute of Marine Fisheries and Oceanography (PINRO) and the Institute of Marine Research (IMR) as the two scientific organisations responsible for research and monitoring the area. The long lasting cooperation between Norway/IMR and Russia/PINRO dates back to the late 1950s with time series for some stocks going back up to 100 years (Jakobsen & Ozhigin, 2011).

Thanks to good collaboration with joint surveys, conferences and exchanging of specialists, the Barents Sea ecosystem and most of its key commercial stocks are today considered to be in relatively good condition, but this has not always been the case. Like most marine ecosystems, the Barents Sea has undergone major changes during the past decades, including collapses and subsequent recoveries of the key species herring and capelin (Dragesund *et al.*, 1997; Hamre, 1994).

The need for an ecosystem approach to fishery management in the Barents Sea became widely recognized after the first known collapse of the capelin stock during the middle of the 1980s. As a key prey for cod in the Barents Sea, changes in capelin stock size hugely impact the cod stock dynamics through changes in growth rate, maturation and cannibalism (Jakobsen & Ozhigin, 2011). NEA cod is well known as being a generalised, opportunistic carnivore, feeding on several types of prey whenever they are available, but during the mid-1980s there was a cold period where most pelagic prey species were scarce. The collapse of the capelin stock had a drastic effect on higher trophic levels. Among the effects were massive invasions of harp seals along the Norwegian coast, high mortality of seabirds, and poor individual growth of cod (Skjoldal *et al.*, 1992).

Capelin is a highly variable stock both in terms of recruitment and spawning stock biomass, and collapses of the capelin stock has shown to happen roughly every 10th year. Today, capelin is therefore fished cautiously with a constant escapement strategy, rather than a F_{MSY} strategy. The fishing occurs after the majority of the cod predation, and thus the fishery is conducted considering the importance of capelin as food for cod (ICES, 2016).

Most fish stocks are today harvested at a rate close to the Maximum Sustainable Yield (MSY), which refers to the maximum equilibrium catch that can be removed from the stock. In modern fisheries, MSY is commonly set to around 30 % of the unexploited population size. As MSY is related to carrying capacity, and hence productivity, the fishery of demersal stocks as a group is fairly balanced by species (Howell *et al.*, 2016).

However, several relatively abundant stocks are not harvested, such as long rough dab (*Hippoglossoides platessoides*) and polar cod (*Boreogadus saida*). Northern shrimp is currently harvested at a low rate, due to market conditions, while capelin is, as mentioned, only lightly harvested. This implies that the fishing intensity is not balanced between all of the key species.

For all fisheries, minimum catch size restrictions apply, usually somewhat below the average size at maturation. Thus, harvesting within species is not balanced; rather a strong “traditional” size selectivity applies. Being one of the best managed fisheries today, the Norwegian fishery represents an example of how traditional fishing regime can work, and thus what BH would have to improve to be worth considering (Howell *et al.*, 2016).

2. Model and methods

2.1 Model

An Atlantis ecosystem model was used to examine the ecosystem responses to a BH fishing regime. The Atlantis model is an ‘end-to-end’ ecosystem model designed to cover the entire ecosystem and integrate all relevant economic and social aspects (Figure 2.1) (Fulton et al., 2011). ‘End-to-end’ models like Atlantis, are aiming at producing realistic simulations of ecosystem dynamics, aiding marine scientists in exploring ecosystem responses under different biological, environmental and fisheries scenarios. Atlantis is currently considered one of the most advanced “what if”-scenario models of aquatic ecosystems in the world (Plagányi, 2007).

The model was initially developed at the Commonwealth Scientific and Industrial Research Organisation (CSIRO) in Australia by Dr. Elizabeth A. Fulton and her team, and have been applied several places around the world, mostly in Australian, U.S, and European waters (Weijerman et al., 2016). Models for other areas are under development (CSIRO, 2017). The model used for this thesis is the Nordic and Barents Sea Atlantis model (hereafter NoBa) developed by Hansen et al. (2016).

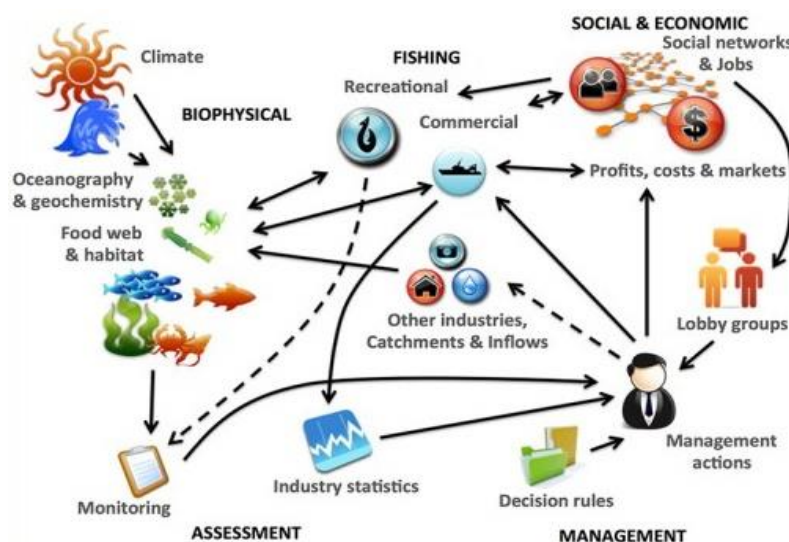


Figure 2.1. A conceptual diagram of the Atlantis model showing the integrated aspects of the management cycle (CSIROscope, 2015)

2.1.1 Spatial distribution

Atlantis is spatially-explicit and simulates spatial variation in both biogeochemical and socio-economic processes. The NoBa domain covers the Nordic Seas (Norwegian, Greenland, Iceland) and the Barents Sea of a total area of 4 million km². This area is divided into 60 polygons, often referred to as boxes, which are relatively homogenous with respect to hydrography, depth and biology (Figure 2.2). There are two main types of boxes; dynamic boxes where all biological and socio-economic processes are modelled, and boundary boxes representing the “outer world” (Audzijonyte *et al.*, 2017a). The boxes are mostly determined by “natural” boundaries, like land and topography (Hansen *et al.*, 2016). The advantage of dividing them like this, rather than in a standard grid, is to match the model geometry to the geographical and bioregional features of the simulated marine system. Smaller, higher-resolution boxes can be defined in areas of particular interest while open water areas can be modelled as one or several large boxes saving a significant amount of computational time (Fulton *et al.*, 2011).

Each box in the NoBa Atlantis model has up to 7 depth layers depending on total depth. If the mean depth of the polygon is more than 1200 m, the lowest depth level will stretch down to the bottom (Hansen *et al.*, 2016). The Barents Sea has a maximum depth of 500 metres, implying that the number of depth layers does not exceed five for this area. On the contrary, the Norwegian Sea has depths of more than 4000 meters, meaning that the seventh layer stretches from 1000 meters and all the way down to the bottom. The layers in the polygons can be specified to represent either water, ice or sediments.



Figure 2.2 Overview of the polygons in the NoBa Atlantis model domain (Hansen *et al.*, 2016)

Atlantis does not calculate water fluxes between the polygons itself but use outputs from specialised oceanographic models. NoBa is forced bottom-up with time series on temperature, salinity, currents (and in some cases ice concentration and thickness) from a Regional ocean modelling system (ROMS: Shchepetkin & McWilliams, 2005) covering the Northeast Atlantic (Skogen *et al.*, 2007).

2.1.2 Functional groups

Currently, the model contains 57 key species and functional groups representing the ecosystems in the Nordic and Barents Seas. These groups involve “everything” from bacteria and zooplankton, to marine mammals and even seabirds. Due to practical reasons and lack of data, all species cannot be included separately in the model. Some must be gathered into functional groups, like “large demersal fish” and “benthic filter feeders”. All species and groups can be found in Table 2.1 and will hereby be referred to as “species”.

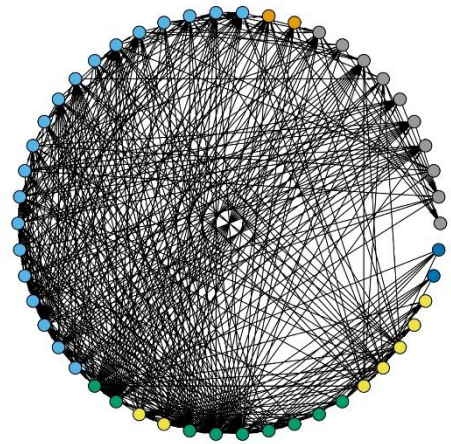


Figure 2.3 Species and functional groups connected through the diet matrix. Grey points represent mammals, orange represent seabirds, blue represent fish, green represent prawns, squid and zooplankton, yellow represent crabs and benthos and dark blue is bacteria (Hansen *et al.*, 2016)

All species are connected through a diet matrix where the proportion of prey available for the predator is defined (Figure 2.3). However, the availability of prey also depends on spatial and temporal overlap, as well as the gape size limit, i.e. the size of the prey compared to the predator. The activity patterns of the predators are also defined for vertebrates and some invertebrate species. If the species activity preference is set to day or night, it will not be active in the model during the other half – it will not initiate ecological processes such as eating, moving or reproducing, but can still be preyed upon (Audzijonyte *et al.*, 2017a). However, there is a loop that ensures that the species eat each day, also during wintertime and summertime with 24 hours of darkness or sunlight (Hansen *et al.*, 2016).

Movement of organisms can be simulated through passive advective transfer (forced by hydrodynamic forcing files), or by direct active movement. While plankton moves passively, vertebrates and pelagic invertebrates can move actively by density-dependent movement

towards high food concentrations, or by forced seasonal migrations within or outside the model domain (Audzijonyte *et al.*, 2017a).

In NoBa, all vertebrates are divided into 10 age classes except for capelin (5) and sperm whale (8). In addition, snow crab is sorted into 6 age classes, while prawns and cephalopods are split into juvenile and adult biomass pools. The remaining invertebrate groups are gathered into biomass pools with no age structure. Currently, the model contains age classes representing whole years (e.g., 1, 2, 5), meaning that vertebrates with a longevity of 25 years are represented by classes of 3 years. Parameters containing information about growth rate, biomass, distribution, recruitment, maturation, longevity, size range, preferred temperature, food source and other factors are all included in the model (Hansen *et al.*, 2016).

Table 2.1 List of species and functional groups included in the NoBa model, with corresponding abbreviations and species the group is parameterised as. The number of years represented in each age class is also included, as well as distribution in the Norwegian Sea (NS), the Barents Sea (BS) or both (NS+BS).

Full name	Abb.	Species included	Years in age class	Distribution
Polar Bear	POB		2	BS
Killer whale	KWH		5	NS
Sperm whale	SWH		5	NS
Humpback whale	HWH		5	NS+BS
Minke whale	MWH		5	NS+BS
Fin whale	FWH		6	NS+BS
Bearded seal	BES		3	BS
Harp seal	HAS		4	BS
Hooded seal	HOS		3	NS
Ringed seal	RIS		3	BS
Arctic seabirds	SBA		2	BS
Boreal seabirds	SBB		2	NS
Sharks, other	SHO	Picked dogfish, Porbeagle, Tope shark	3	NS+BS
Skates and rays	SSK	Arctic skate, starry ray, sailray, longnosed skate, thornback ray, round skate, spinytail skate	2	NS+BS
Demersals, other	DEO	Ling, Tusk	2	NS+BS
Pelagic large	PEL	Atlantic salmon	1	NS+BS
Pelagic small	PES	Lumpfish, Norway pout	1	NS+BS
Redfish, other	REO	Golden redfish	4	NS+BS
Demersal, large	DEL	Monkfish, Atlantic halibut, Atlantic wolffish, northern wolffish, spotted wolffish	2	NS+BS
Flatfish, other	FLA	European plaice, common dab, winter flounder	2	NS+BS
Long rough dab	LRD		2	NS+BS
Mesopelagic fish	MES	Silvery lightfish, glacier lantern fish	1	NS+BS
Greenland halibut	GRH		2	NS+BS
Mackerel	MAC		2	NS
Haddock	HAD		2	NS+BS

Saithe	SAI		2	NS+BS
Redfish	RED		4	NS+BS
Blue whiting	BWH		1	NS+BS
Norwegian Spring Spawning herring	SSH		2	NS
Northeast Arctic cod	NCO		2	NS+BS
Polar cod	PCO		1	BS
Capelin	CAP		1	BS
Prawn	PWN	<i>Pandalus borealis</i>	-	BS
Cephalopods	CEP	<i>Gonatus fabricii</i>	-	NS+BS
Red king crab	KCR		-	BS
Snow crab	SCR		1	BS
Gelatinous zooplankton	ZG	<i>Aurelia aurita, cyanea capillata</i>	-	NS+BS
Large zooplankton	ZL	<i>Thysanoessa inermis</i>	-	NS+BS
Medium zooplankton	ZM	Parameterized as <i>Calanus finmarchicus</i>	-	NS+BS
Small zooplankton	ZS	Small copepods, oncaea, pseudocalanus (<i>Oithona similis</i>)	-	NS+BS
Dinoflagellates	DF		-	NS+BS
Small phytoplankton	PS	Flagellates	-	NS+BS
Large phytoplankton	PL	Diatoms	-	NS+BS
Predatory benthos	BC	Echinoderms, sea urchins, annelids and anemones	-	NS+BS
Detrivore benthos	BD	Selected annelids, echinoderms	-	NS+BS
Benthic filter feeders	BFF	Selected molluscs, barnacles, moss animals, anemones (<i>Tridonta borealis</i>)	-	NS+BS
Sponges	SPO	<i>Geodia baretii</i>	-	NS+BS
Corals	COR	<i>Lophelia pertusa</i>	-	NS+BS
Pelagic bacteria	PB		-	NS+BS
Benthic bacteria	BB		-	NS+BS
Refractory detritus	DR		-	NS+BS
Carrion	DC		-	NS+BS
Labile detritus	DL		-	NS+BS

2.1.3 Growth

The model tracks the flow of nutrients through the trophic levels using nitrogen as the currency, although phosphorous and carbon may also be used. The weights of all vertebrates and invertebrates are defined in terms of mg nitrogen (mg N), with the weights of vertebrates divided into structural (SN), and reserve weights (RN). SN represents bone weight and RN represents soft-tissue weight. The separation between the two enables tracking the size and condition of the animals separately, to detect whether the animals are starving or not (Hansen *et al.*, 2016).

Growth is different for age-structured vertebrates and biomass-pooled invertebrates. For invertebrates, the growth is determined by the food intake and an assimilation efficiency. The assimilation efficiencies vary for different food types (live, plant, labile detritus and refractory detritus). Vertebrate groups have additional maintenance or respirational costs (R_s), and the remaining energy is allocated to SN and RN, i.e. to growth. The SN pool cannot decrease, whereas the RN pool can decrease, as it is used for reproduction and for meeting optional maintenance needs if assimilated food is insufficient. Both vertebrates and invertebrates have a maximum growth rate. The realised growth and size of species represented in the age-structured groups rely on food intake, while feeding interactions and reproductive output depends on the realised size and condition.

The unconsumed food (faeces) and non-predation mortality products are sent to labile detritus (DL), refractory detritus (DR), carrion (DC) and ammonia (NH) pools. The waste produced by vertebrates and invertebrates is handled in the same way, but for vertebrates the mortality terms are converted from the number of individuals to biomass before being used (Audzijonyte *et al.*, 2017a).

2.1.4 Recruitment

Recruitment and the recruitment success of stocks are generally difficult to predict. Therefore, these are estimated to a higher degree in the model than from literature in order to achieve stable abundance levels (Hansen *et al.*, 2016). There are several options for how the recruits enter the model. Most fish species in the model has recruitment based on the classic Beverton-Holt equation (Beverton & Holt, 1957):

$$R = \frac{aS}{1+bS} < \frac{a}{b} \quad (2.1)$$

Where the recruitment (R) depends on spawning stock size (S) and a density-independent parameter (a) and a density-dependent parameter (b). The exceptions to this recruitment option are polar cod and capelin, which have a Beverton-Holt relationship with log-normal variation added, and the Norwegian Spring Spawning herring which uses Beverton-Holt, but with a possibility of strong year classes. For mammals, birds and some sharks, each adult is assumed to have a fixed number of pups/calves and a constant number of recruits per adult is used (Hansen *et al.*, 2016).

The number of recruits is influenced by the amount of spawn produced, stock biomass, phytoplankton, zooplankton and/or external recruitment forcing. Recruited individuals are applied to the first year of the first age group. The day before the recruits "arrive", all other individuals age one year up, and are assigned to a different age group (Audzijonyte *et al.*, 2017a).

Atlantis does not distinguish between males and females but represents an average individual where all individuals in a biomass pool or an age class are considered identical in terms of reproductive output. Sexual maturation in vertebrate groups is determined by age and length. Each age class are given a fraction that is set as sexually mature, and an optional minimum length required for sexual maturation. The amount of spawn each group produce is determined according to the condition of individuals in the age group at the time of spawning. This is done by defining an optimum spawning weight of an age group based on the ratio of RN to SN. Atlantis does not model the larval period. Instead, the nitrogen produced as spawn is temporarily taken out of the model and then returned as recruits after a set larval period (Audzijonyte *et al.*, 2017a).

2.1.5 Mortality

In Atlantis, the mortality is divided into natural mortality, predation mortality and fisheries mortality, the latter given that the harvesting module is turned on. The natural mortality accounts for mortality due to old age and diseases, and is generally very low compared to the predation mortality. Due to this, the mortality levels found in the literature are not directly useable, and the values used in NoBa are therefore estimated based upon tuning to avoid extinctions and obtain reasonable estimates of abundances in comparisons to observed values (Hansen *et al.*, 2016).

Atlantis have additional terms of mortality related to starvation, oxygen limitation and ocean acidification. Starvation mortality is only available for age-structured vertebrates, as the condition (ratio of SN to RN) is tracked for these groups only (Audzijonyte *et al.*, 2017a). In NoBa, mortality due to oxygen limitation and ocean acidification is only used for long-term climate projections (Hansen *et al.*, 2016). The mortality is modelled differently for vertebrates and invertebrates. Mortality in vertebrate groups is modelled as the number of individuals lost, whereas for invertebrates it is expressed as biomass lost. At the end of the lifespan, the

individuals (or biomass) can either all die or remain in the last cohort for as long as they survive predation or other mortality factors. For top predators, such as mammals, predation mortality alone is typically too low to impose adequate control. In these cases, higher terms of natural mortalities are applied (Audzijonyte *et al.*, 2017a).

2.1.6 Socio-economics

Atlantis is intended for management strategy evaluation and contains representations of every vital component in the adaptive management cycle. All of the components have a dynamic, two-way coupling that allows for interaction between the sub-models (Figure 2.4) and are divided into a:

1. Harvest sub-model – Human use of the system
2. Management sub-model – Which includes the three major components of a management strategy:
 - Monitoring
 - Assessment
 - Management decision
3. Economic sub-model – Socioeconomic drivers of human use and behaviour.

The Biophysical sub-models are obligatory, whereas the Harvest, Management and Economics sub-models are optional, implying that simulations can be run without any explicit exploitation or human impact. Still, given that most marine areas today are influenced by human activities in some way, and that one of Atlantis main purposes is to study how this affects marine life, this is a central part of the model.

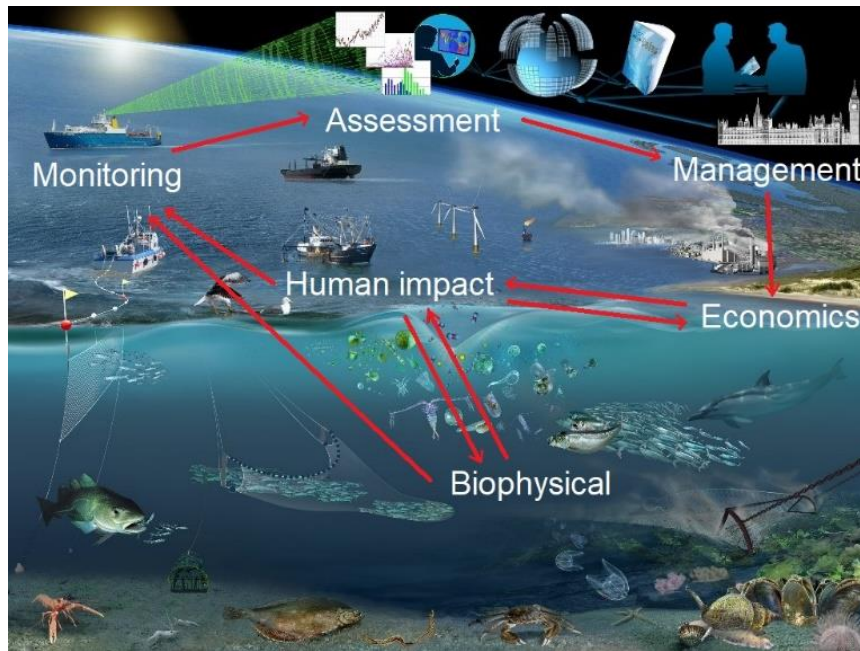


Figure 2.4 Schematic figure of the major sub-groups and connections included in the Atlantis modelled framework (Modified from <https://www.masts.ac.uk/>, 2018)

The harvest sub-model deals with the human exploitation of the marine ecosystems, with a main focus on the dynamics of fishing fleets. It allows for multiple fleets with its own set of characteristics like gear selectivity, habitat association, target species, effort allocation and management structures. All forms of fishing may be represented, including recreational fishing which is determined by the human population in the area (Fulton *et al.*, 2011). The NoBa Atlantis model currently includes 27 fisheries with distinct characteristics and commercially targeted species (Table 2.3). In addition to fishing fleets, simple representations of human exploitation other than fishing, like pollution, shipping, coastal development or broad-scale environmental changes, may also be represented through forcing (Audzijonyte *et al.*, 2017a).

The management sub-model is used to regulate the fishing effort according to rules and restrictions by applying gear limitations, quotas, days at sea, discarding restrictions and bycatch reduction. (Audzijonyte *et al.*, 2017b). The economics sub-model tries to capture the socio-economic pressures that control harvesting decisions and include fish prices, taxes, penalties and fishing costs, but is an optional feature in Atlantis not used in this project.

2.2 Methods

2.2.1 Calculating productivity and fishing mortalities

Implementation of BH requires information on the production of all species, as BH is designed to exert fishing mortality in proportion to natural productivity. However, the literature does not provide a single clear measure of how the production should be used to set fishing mortality (Heath *et al.*, 2017).

In the paper of Garcia *et al.*, (2012) where BH was first defined, production is described as the individual growth plus recruitment, i.e. the amount of living material produced each year. The growth in the Atlantis model include the “young of year” coming into the system in age group 1, and thereby encompass both growth and recruitment, i.e. the total production. The production is then divided by biomass to get a “per capita” rate, often referred to as P/B-ratio, and eventually multiplied by a constant to set the proportional fishing mortality. This approach, setting fishing mortality proportional to the P/B ratio, is one of the alternatives suggested amongst BH-scientists (Jacobsen *et al.*, 2014; Kolding *et al.*, 2016) and will therefore be used for this thesis.

Calculation of the P/B ratio, hereafter referred to as “productivity”, was done using data from the model output files generated by an initial run where historical fishing mortalities were applied. This run was set up prior to this study by C. Hansen, with the intent of representing the historical fisheries in the most realistic way. All model outputs were read and processed by means of “R studio” (RStudio Team, 2015) under version 3.4.0 (“You Stupid Darkness”), run on a Windows machine.

Calculating the productivity by means of the Atlantis model turned out to be a far greater challenge than expected. Several approaches were applied, and these are listed in the Appendix 1, Table A.1. The problems were caused mainly by the fact that some species migrate outside the model domain during the year, and thereby have zero growth and biomass during this time in addition to no information on the “young of year”. The problem was eventually solved by printing the data out five times a year (every 73rd day) instead of once a year.

The NoBa model is initiated at early 1980s levels, as the physical forcing is available from 1981, and it was decided to run the model until 2031 to give the fisheries a chance to stabilise.

To capture the yearly variations in productivity, the productivity was calculated for each year from 1981 to 2030. As many other ecosystem models, Atlantis need to run for a number of years to "spin-up" processes, stabilise interactions, remove excessive influence of initial conditions on fast turnover properties and to allow for more reasonable age structures to become established (Olsen *et al.*, 2016). The NoBa model has a spin-up time of 24 years. As the values during the spin-up time are not reliable, the 24 first years were removed before calculating the productivity levels.

Information on growth, weight and numbers was needed to estimate the productivity and biomass of age-structured vertebrate groups. Both growth (g) and weight (w) are given in mg N and had to be converted to tonnes wet weight biomass. By means of Equation 2.2, which is specific for the Atlantis model (Fulton E. A *et al.*, 2004), the structural and reserve nitrogen (RN and SN) were added up and converted to wet weight in tonnes (w) as:

$$w = (RN + SN) \cdot \frac{k_{wetdry} \cdot X_{CN}}{10^9}, \quad (2.2)$$

where k_{wetdry} is the wet weight to ash free dry weight ratio, typically set to 20 based on carbon as a proxy for dry weight, and X_{CN} is the carbon to nitrogen Redfield ratio usually set to 5.7. The equation was then divided by 10^9 from mg to tonnes, for further calculations of biomass.

$$B = w \cdot n \quad (2.3)$$

Subsequently, the biomass (B) was calculated by multiplying the average weight (w) with the corresponding abundance (n). The production was defined through the following equation:

$$P = g \cdot 365 \cdot n \quad (2.4)$$

The individual growth pr. day (g) had to be converted to tonnes through Equation 2.2, and then multiplied by 365 days and corresponding abundance (n) to get the overall growth pr. year, i.e. the total yearly production (P). The production was then divided on the biomass to get a P/B-ratio referred to as productivity. For invertebrates the production, given in nitrogen N [mg/m³], was retrieved directly from the model, as well as the biomass (as invertebrates are gathered given as biomass pools).

$$\frac{P}{B} = \frac{p \cdot V}{B} \quad (2.5)$$

Thus, the overall production (P) was calculated by multiplying the volume (V) of each box by this production (p). The transformation in Equation 2.2 was used for transformation to tonnes, and the total production was divided by biomass (B) to get the productivity. The productivity was calculated throughout each year to capture the yearly variations within the model and converted to a fishing mortality by the following equation:

$$F_{BH} = c \cdot \frac{P}{B} \quad (2.6)$$

The productivity ($\frac{P}{B}$) was multiplied with a dimensionless constant, c , determining the intensity of exploitation. Based on the Cadima estimator (Troade, 1977) and Kolding (1994) it was decided to use a constant of 0.25, corresponding to 25 % harvest of the stock's annual production. Atlantis has several ways of applying fishing mortality. For this purpose, the best option was a fishery-induced mortality rate where a proportion of biomass is set to be harvested each day. The actual catch biomass would then depend on the species abundance and fishing parameters.

2.2.2 Balance over sizes – Applying selectivity curves

As BH aims to balance over sizes as well as species, a size-specific selectivity had to be applied to all age-structured groups. This was done by taking the mean productivity of each age group throughout the simulated years (i.e. year 25-73, with spin-up years 1-24 removed).

Atlantis has different options for defining selectivity of the fishing gear to exert a greater fishing pressure on certain sizes. It was decided to use a logistic length-based selectivity curve, which is one of the most commonly applied selectivity options, often applied for trawl nets where the fraction of retained fish depends on the size of the fish. The selectivity curve usually follows the shape of a sigmoid curve ranging from 0 to 1, where the possibility of retention at lengths span from 0 % to 100 % (Sparre & Venema, 1998). The equation is given as:

$$p_{sel}_i = \frac{1}{1 + \exp(-sel_b \cdot (L - lsm))} \quad , \quad (2.7)$$

where the inflection point (lsm) is the length at 50 % selectivity where 50% escape and 50% are retained (Figure 2.5a). The other parameter ($selb$) determines the steepness of the curve (Figure 2.5b). To determine these two, the lengths (L) of the different age classes needed to be calculated. As Atlantis is age-based rather than size-based, all age groups were converted to size-groups by solving the length-weight relationship equation (Hile, 1936; Martin, 1947) with respect to length:

$$W = a \cdot L^b \rightarrow L = \sqrt[b]{\frac{W}{a}} \quad (2.8)$$

The lengths (L) were determined by two species dependent parameters, (a) and (b), collected from literature and applied in the model (Hansen *et al.*, 2016), and the weight (W) was calculated by adding the structural and reserve weights from the output files using Equation 2.2. To find the best values for lsm and $selb$, a non-linear least square regression was done in R studio, where the sum of squares of the distances from the data to the regression curve is minimised. By assuming some initial start values for lsm and $selb$ and applying the selectivity curve equation (Equation 2.7), the lsm and $selb$ values giving the selectivity curve closest to the productivity levels were selected.

Figure 2.5 shows an example of how lsm and $selb$ affect the shape of the selectivity curve of haddock. The length values (L) for the different age classes were plotted into a graph with the mean productivity levels at each length (converted from age). The productivity levels were then scaled to fit the 0-1 scale of the selectivity curve, and various options of the selectivity curve defined by Equation 2.7, was plotted in to show the effects of lsm and $selb$.

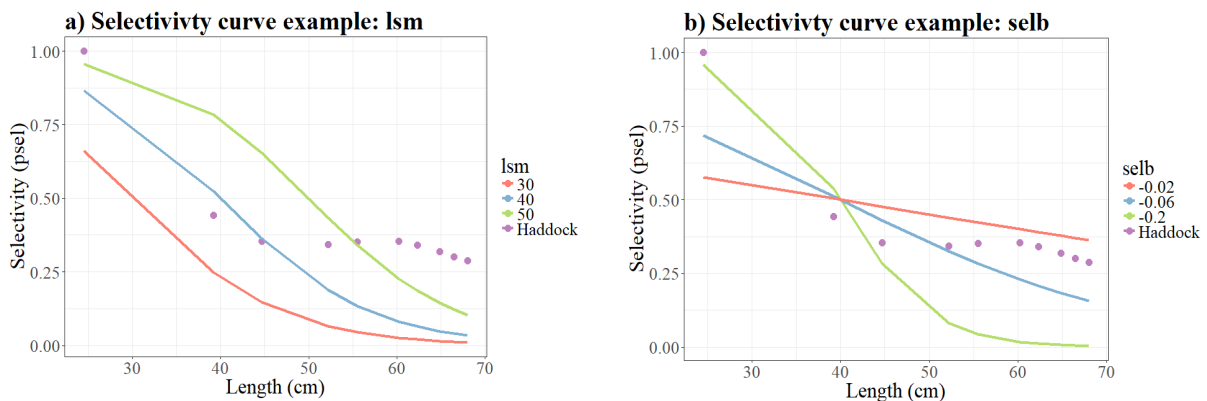


Figure 2.5. The logistic gear selectivity curve can be modified to fit the productivity levels at size. Figure (a) shows variations in lsm affecting the inflection point while keeping $selb$ constant, and figure (b) shows variations of $selb$ affecting the steepness of the curve while keeping lsm constant.

The productivity is typically considered to decrease as a function of body size (Peters, 1986), suggesting a selection curve where a greater amount of small sizes are caught. This contradicts the traditional selectivity curve which aims to protect the young, i.e. smaller sizes, and target larger sizes. The initial start value of *selb* in the non-linear ls regression performed in R was therefore set to -0.1, with negative value indicating a descending curve.

As a rule of thumb, the initial start value of *lsm* was set as the minimum allowed catch size (Fiskeridirektoratet, 2017). In cases where this was not suitable, or for species with no information on min. catch size, visual observations determined the starting values. A table of all *lsm* and *selb* values can be found in the Appendix 2, Table A.5 as well at the selection curves of all age-structured groups (Appendix 2, Figure A.2).

Young age classes are generally hard to model and possess great uncertainty, as there is little knowledge on abundance and mortality. This is because they are difficult to survey and have a variable, high, natural mortality. When studying the mean productivity of each age class it became apparent that the productivity of age class 1 for all groups was considerably higher, which affected the mean estimated productivity, and thereby the fishery mortality (Table 2.2) and made it difficult to fit the selection curves (Figure 2.6). It was therefore decided to exclude age class 1 from the calculations. A comparison of with and without age class 1 can be found in Appendix 1, Table A.4.

Table 2.2 List of mean productivity of each age class of Northeast Arctic cod shows the productivity of age class 1 being 20 times higher compared to remaining age classes

Age class	Mean productivity
1	23.63
2	1.35
3	1.39
4	1.41
5	1.33
6	1.39
7	1.32
8	1.23
9	1.11
10	1.04

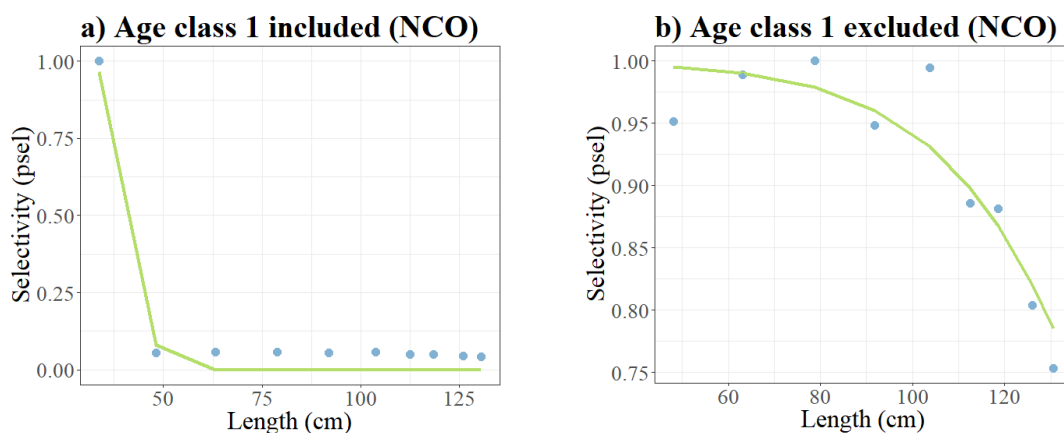


Figure 2.6 Selectivity curve of Northeast Arctic cod (NCO) demonstrating the difficulties of fitting a curve when all age groups are included (a), as opposed to when age class 1 is excluded (b). Note that the scale of the y-axis differs for the two plots.

2.2.3 Running the model

The runs were separated into two categories, depending on the species subjected to BH:

1. Balanced harvesting on commercial species
 - In the Norwegian Sea
 - In the Barents Sea
2. Balanced harvesting on “non-commercial” species
 - On lower trophic levels and small fish
 - On higher trophic levels and large fish

The balanced harvest of species categorized as “non-commercial” were either unexploited or lightly exploited species that were not harvested in the model control run and will hereafter be referred to as “non-commercial”. Some combined runs were conducted to explore the accumulated effects of BH on all selected species across ecosystems and trophic levels. The species selected are shown in Table 2.3. Species 1-12 are currently commercially exploited and were already harvested in the control run set up by C. Hansen.

Table 2.3 List of species chosen to be exposed to BH through this project, with adjoined codes of modelled fishing fleets. The selectivity option of the fishing gear was applied to all age-structured components

No	Species	Fishing fleet	Selectivity curve
1	<i>Norwegian spring spawning herring</i>	pseineSSH	Yes
2	<i>Blue whiting</i>	pseineBWH	Yes
3	<i>Mackerel</i>	pseineMAC	Yes
4	<i>Northeast Arctic cod</i>	dtrawlNCO	Yes
5	<i>Capelin</i>	pseineCAP	Yes
6	<i>Haddock</i>	dtrawlHAD	Yes
7	<i>Saithe</i>	dtrawlSAI	Yes
8	<i>Greenland halibut</i>	dtrawlGRH	Yes
9	<i>Redfish</i>	dlineNCO	Yes
10	<i>Redfish other</i>	dlineSAI	Yes
11	<i>Snow crab</i>	dlineHAD	Yes
12	<i>Prawns</i>	dtrawlPWN	No
13	<i>Zooplankton medium</i>	dlineGRH	No
14	<i>Zooplankton gel</i>	dlineGRH	No
15	<i>Mesopelagic fish</i>	dseineNCO	Yes
16	<i>Polar cod</i>	dseineHAD	Yes
17	<i>Pelagic small</i>	dseineSAI	Yes
18	<i>Benthic filter feeders</i>	dseineGRH	No
19	<i>Skates and rays</i>	netNCO	Yes
20	<i>Long rough dab</i>	netHAD	Yes
21	<i>Demersal large</i>	netSAI	Yes
22	<i>Demersals other</i>	netGRH	Yes
23	<i>Minke whale</i>	cullMWH	Yes

A total of 108 model runs were conducted for this thesis. Table 2.4 lists the 56 runs that were selected for analysis, while a complete list of all runs can be found in the Appendix 3, Table A.6. To explore the ecosystem responses to a BH fishing regime, the runs were carefully set up to track the effects by adding one species at the time. All runs were performed by modifying the control run through adjustments of fishing effort and by adding selection curve features. The commercial species that were not subjected to BH was harvested according to the fishing mortalities in the control run (Table 3.1) with a flat constant selectivity option applied.

The runs were first separated into BH on commercial and non-commercial species. Simulations conducted on commercial species was then divided based on geographic distribution, i.e. the Norwegian Sea and the Barents Sea. In the Norwegian Sea where only three fish species are commercially harvested, all combinations could be tested, while in the Barents Sea the runs were conducted on one species at a time, and thereafter by adding one species to a combined run where eventually all selected species in the Barents Sea was harvested. Subsequently, balanced harvesting in the Barents Sea and the Norwegian Sea was combined, both with and without prawns included (due to some model problems with the trophic links between prawns and other stocks, see discussion).

The non-commercial components were also separated into two groups; one on lower trophic levels including zooplankton, benthic filter feeders, jellyfish and small fish, and one other group of higher trophic levels including large demersal fish, skates and minke whale. The non-commercial group consisted of species that were either lightly harvested (e.g. Calanus, minke whale, ling and tusk) or unexploited species.

Table 2.4 List of all simulations selected for analysis (see Table 2.1 for species codes)

Simulations	Description
run_00	Control run with historical fisheries applied
run_41	BH on MAC
run_42	BH on SSH
run_43	BH on BWH
run_44	BH on MAC + SSH
run_45	BH on SSH + BWH
run_46	BH on BWH + MAC
run_47	BH on MAC, SSH, BWH (The Norwegian Sea)
run_48	BH on NCO
run_49	BH on CAP
run_50	BH on HAD
run_51	BH on SAI
run_52	BH on GRH
run_53	BH on RED
run_54	BH on REO
run_55	BH on SCR
run_39	BH on PWN
run_62	BH on NCO, CAP, HAD, SAI, GRH, RED, REO + SCR (The Barents Sea)
run_64	BH on Barents Sea + MAC
run_65	BH on Barents Sea + SSH
run_66	BH on Barents Sea + BWH
run_67	BH on Barents Sea + MAC+SSH
run_68	BH on Barents Sea + SSH+BWH
run_69	BH on Barents Sea + BWH+MAC
run_70	BH on all commercial species (The Norwegian and Barents Seas)
run_71	BH on all commercial + ZM (x 0.15)
run_72	BH on all commercial + ZG
run_73	BH on all commercial + MES
run_74	BH on all commercial + PCO
run_75	BH on all commercial + PES
run_76	BH on all commercial + BFF
run_77	BH on all commercial + ZM (x 0.15), ZG, MES, PCO, PES, BFF
run_78	BH on all commercial + SSK
run_79	BH on all commercial + LRD
run_80	BH on all commercial + DEL
run_81	BH on all commercial + DEO
run_82	BH on all commercial + MWH
run_83	BH on all commercial + SSK, LRD, DEL, DEO, MWH
run_84	BH on all species (NB! PWN excluded, ZM x 0.15)
run_85	BH on ZM
run_85_5	BH on ZM (x 0.50)
run_85_2	BH on ZM (x 0.25)
run_85_1	BH on ZM (x 0.15)
run_86	BH on ZG
run_87	BH on MES
run_88	BH on PCO
run_89	BH on PES
run_90	BH on BFF
run_91	BH on ZM (x 0.15), ZG, MES, PCO, PES, BFF
run_92	BH on SSK
run_93	BH on LRD
run_94	BH on DEL
run_95	BH on DEO
run_96	BH on MWH
run_97	BH on SSK, LRD, DEL, DEO, MWH
run_98	BH on ZM (x 0.15), ZG, MES, PCO, PES, BFF, SSK, LRD, DEL, DEO, MWH

2.2.4 Analysis

The runs in this study covered a period of 27 010 days corresponding to 74 years of 365 days. This included a spin-up time of 24 years which constituted 14 years without any fishery, followed by ten years where a spin-up fishery was applied. Consequently, the BH was introduced to the 25th year, while spin-up years were preserved to make it comparable to the historic run. Unfortunately, due to a bug in the model code, the selectivity applied in later years affected the spin-up period during the time in which the spin-up fisheries occur. All plots in the results therefore include the last ten years of spin-up.

All plotting was carried out through “R studio” (RStudio Team, 2015) under version 3.4.0. The analysed output of the data was produced for January each year, as the catch output could only be printed for the first day of the year with the model version used. For ecosystem plots of functional groups, an R-script developed by Isaac Kaplan, Gavin Fay and Kelli Johnson for Olsen *et al.* (2018), was used, and the species and functional groups belonging to each guild in the plots can be found in Table 2.5.

Table 2.5 List of all components assigned to functional groups in the ecosystem plot used for the results

Guild:	Species/functional groups:
Mammal	Killer whale, Sperm whale, Humpback whale, Minke whale, Polar bear
Seabird	Seabird arctic, Seabird boreal
Shark	Sharks other, Skates rays
Demersal fish	North Atlantic cod, Greenland halibut, Haddock, Demersal other, Demersal large, Redfish, Redfish other, Flatfish other, Long rough dab, Skates rays, Polar cod
Pelagic fish	Large pelagic, Small pelagic, Mesopelagic fish, Mackerel, Saithe, Blue whiting, Norwegian Spring Spawning herring, Capelin
Squid	Squid
Filter feeder	Sponges, Corals, Benthic filter feeders
Epibenthos	Snow crab, King crab, Prawns
Zooplankton	Small zooplankton, Medium zooplankton, Large zooplankton, Gel zooplankton
Primary producers	Dinoflagellates, Small phytoplankton, Large phytoplankton
Infauna	Predatory benthos, Detrivore benthos

3. Results

In the following, results are presented through changes in biomass, catch and age-structure of species and functional groups. The first part includes the results of implementing BH on commercial species in the Norwegian and Barents Sea respectively, while the second part focuses on the effects of expanding a BH regime to include species on lower and higher trophic levels that are not commercially exploited today. The third and last part covers some combined runs to show the total effects of a BH regime on all harvested species with focus on total yields. The results are generated by the NoBa Atlantis model and must be evaluated in terms of the assumptions and limitations of such models. Due to a bug in the code, the selectivity was applied during the last 10 years of the spin-up, and this part is therefore included in all plots with a line representing where the actual simulations start. It should be noted that the results are based on visual observations of trends in the model and has not been tested statistically.

3.1 Balanced harvesting on commercial species

The calculated fishing mortalities for all commercial species are shown in Table 3.1 together with the historical fishing levels and the differences between the two.

Table 3.1 Calculated BH fishing mortalities (F_{BH}) of 25% of the productivity for all commercial species, including the historical fishery mortalities (F_{Histo}) applied in the control run, and the difference in percent

Species	F_{Histo}	F_{BH}	Difference
<i>Mackerel</i>	3.452	1.121	- 68 %
<i>Norwegian S.S herring</i>	0.104	0.169	+ 62 %
<i>Blue whiting</i>	0.175	0.561	+ 221 %
<i>Northeast Arctic cod</i>	0.233	0.308	+ 32 %
<i>Capelin</i>	0.038	0.357	+ 841 %
<i>Haddock</i>	0.237	0.283	+ 19 %
<i>Saithe</i>	0.231	0.337	+ 46 %
<i>Greenland halibut</i>	0.028	0.228	+ 719 %
<i>Redfish</i>	0.015	0.115	+ 673 %
<i>Redfish other</i>	0.216	0.066	- 70 %
<i>Snow crab</i>	0.040	0.367	+ 812 %
<i>Prawns</i>	0.011	6.414	+ 59288 %

3.1.1 Norwegian Sea

The main commercial species in the Norwegian Sea were the large pelagic stocks of mackerel, blue whiting and Norwegian Spring Spawning herring (hereafter herring). The effects of different combinations of balanced harvesting in the Norwegian Sea (Figure 3.1) reflected the changes in fishing mortalities (Table 3.1), as mackerel showed an increase in biomass due to a lower fishing pressure, while the biomasses of blue whiting and herring decreased due to a higher fishing pressure (hereafter expressed as the instantaneous fishing mortality F).

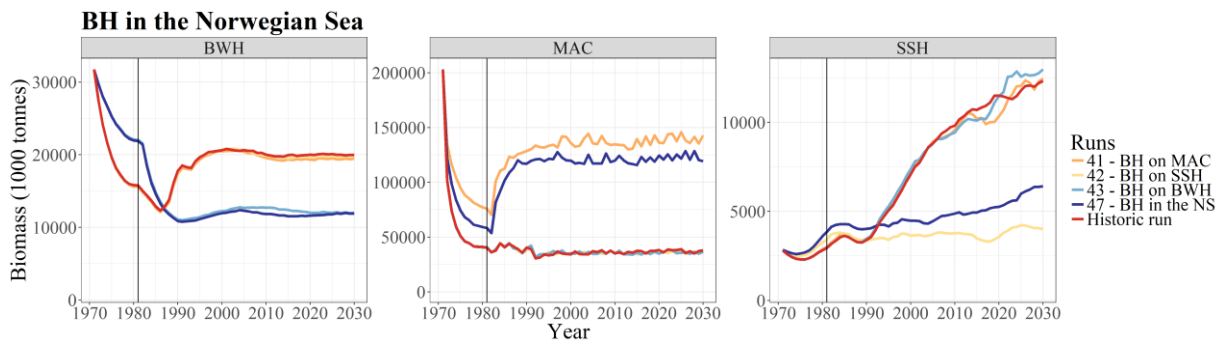


Figure 3.1 Development of biomass over time indicate that BH had an increasing effect on mackerel (MAC), in contrast to a decreasing effect on the biomasses of blue whiting (BWH) and spring spawning herring (SSH).

The productivity of mackerel was calculated strikingly high compared to the other vertebrate groups (Table 3.1). However, the calculated F_{BH} was just about a third of F_{Histo} , resulting in a lower fishing pressure on mackerel during a BH regime. This was because mackerel migrate outside the model domain, and the fishing pressure was therefore scaled up in the historic run. It was attempted to scale the F_{BH} by multiplying the fishing pressures with the same ratio as in the historic run (Appendix 1, Figure A.1). However, given the high calculated productivity, this caused an instant collapse and the runs were not included in the thesis.

Figure 3.2 show the changes in biomass for each guild compared to the control run of the current fishing pressure and pattern. The most obvious impacts were in the group of “pelagic fish”, which includes the three species that was harvesting according to BH.

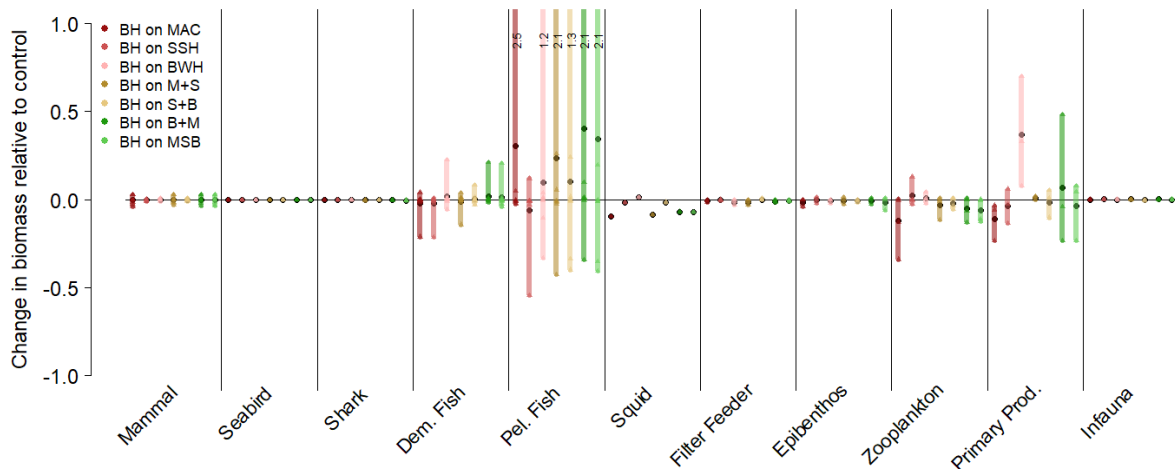


Figure 3.2 The effects on the biomass of each guild due to balanced harvesting on commercial species in the Norwegian Sea, i.e. mackerel (MAC), Norwegian spring spawning herring (SSH) and blue whiting (BWH). The bars show the change in biomass compared to the initial control run where historical fisheries were applied.

Primary producers were positively affected by harvesting on blue whiting, while zooplankton was negatively affected when harvesting mackerel. By examining the effects on other pelagic fish, it was uncovered that mesopelagic fish (MES) increased in biomass in all runs which involved blue whiting, i.e. runs that resulted in a reduced biomass of blue whiting (Figure 3.3).

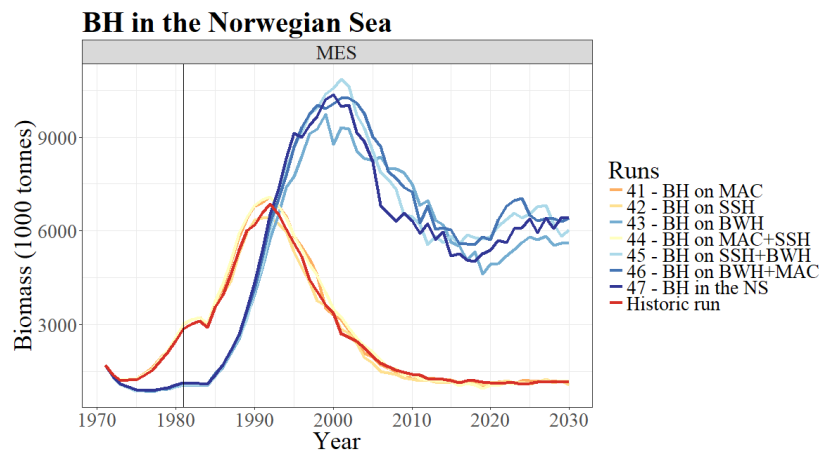


Figure 3.3 The effects of BH in the Norwegian Sea on mesopelagic fish (MES). All blue lines involve harvesting on blue whiting (BWH)

3.1.2 Barents Sea

BH in the Barents Sea involved more species than in the Norwegian Sea. The main commercial species are the Northeast Arctic cod (hereafter NEA cod), capelin, haddock, saithe, Greenland halibut, two groups of redfish including beaked redfish and golden redfish, in addition to prawns and snow crab. When studying the ecosystem plot (Figure 3.4), the most profound effect of BH on other species, including mammals, was the BH on prawns, more specifically *Pandalus borealis*.

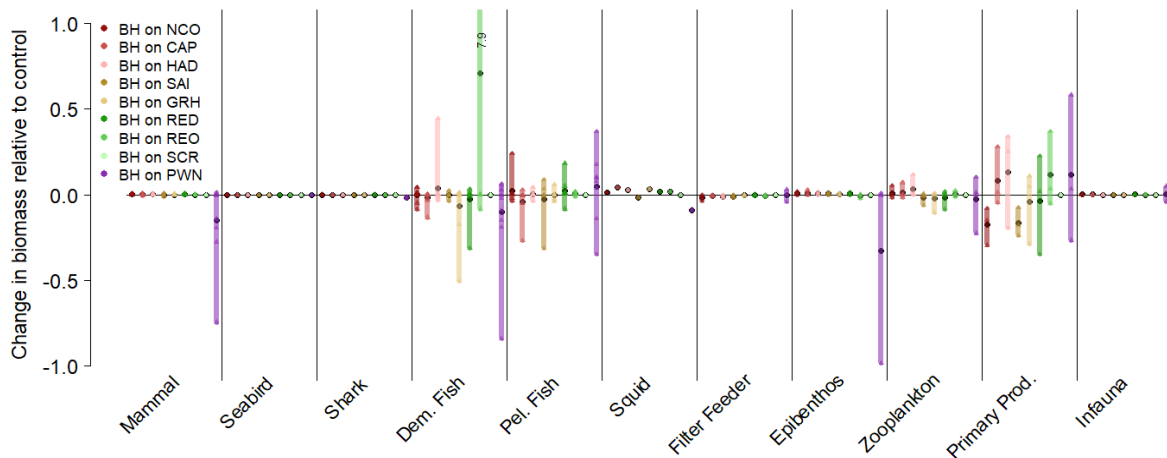


Figure 3.4 The effects on the biomass of each guild due to balanced harvesting on commercial species in the Barents Sea, i.e. on Northeast Arctic cod (NCO), capelin (CAP), haddock (HAD), saithe (SAI), Greenland halibut (GRH), beaked redfish (RED) golden redfish (REO) snow crab (SCR) and prawns (PWN). The bars show the relative change in biomass compared to the initial control run were historical fisheries were applied.

The fishing mortalities calculated on prawns were nearly 600 times higher compared to historical fisheries (Table 3.1), causing an immediate collapse when applied after the spin-up time (Figure 3.5).

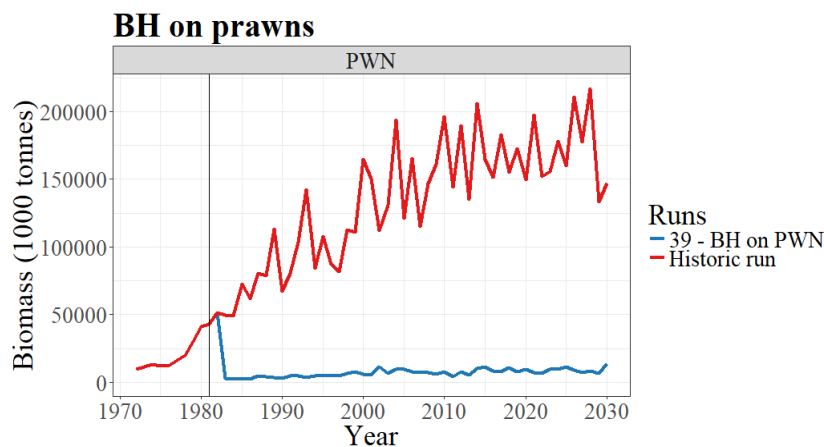


Figure 3.5 Balanced harvesting on prawns (PWN) cause an instant collapse of the population

The collapse of prawns had strong cascading effects throughout the ecosystem (Figure 3.6). By effectively removing the prawns from the food chain, the biomasses of higher trophic level species were severely reduced, even on marine mammals like fin whale and minke whale. This had various cascading effects through the ecosystem, such as a higher abundance of pelagic prey fish.

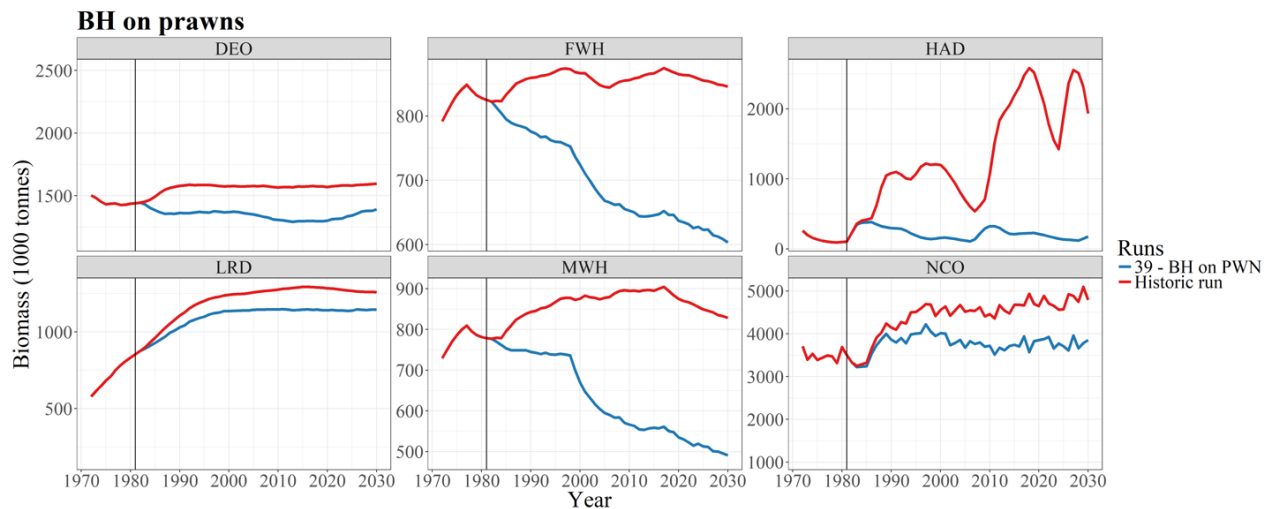


Figure 3.6 Examples of higher trophic level species, like fin whale (FWH), haddock (HAD), killer whale (KWH), long rough dab (LRD), minke whale (MWH) and Northeast arctic cod (NCO), affected by the absence of prawn (PWN)

It was decided to exclude BH on prawns, as the results suggested an unreasonably high fishing mortality in addition to an over-dependency on prawns by other species. The harvesting of prawns was therefore kept at historic levels through all the following runs. In addition, a mistake made in the initial control run caused the snow crab to remain historically unharvested through all runs, while saithe behaved strangely in the model. This has now been corrected in a newer update of the Atlantis model (not used here). In the following, plots of prawns, saithe and snow crab are therefore not included.

Figure 3.7 highlighted the same trend as seen in the Norwegian Sea, namely that the biomass of all species was most affected by the direct harvest on that particular species (except for prawns).

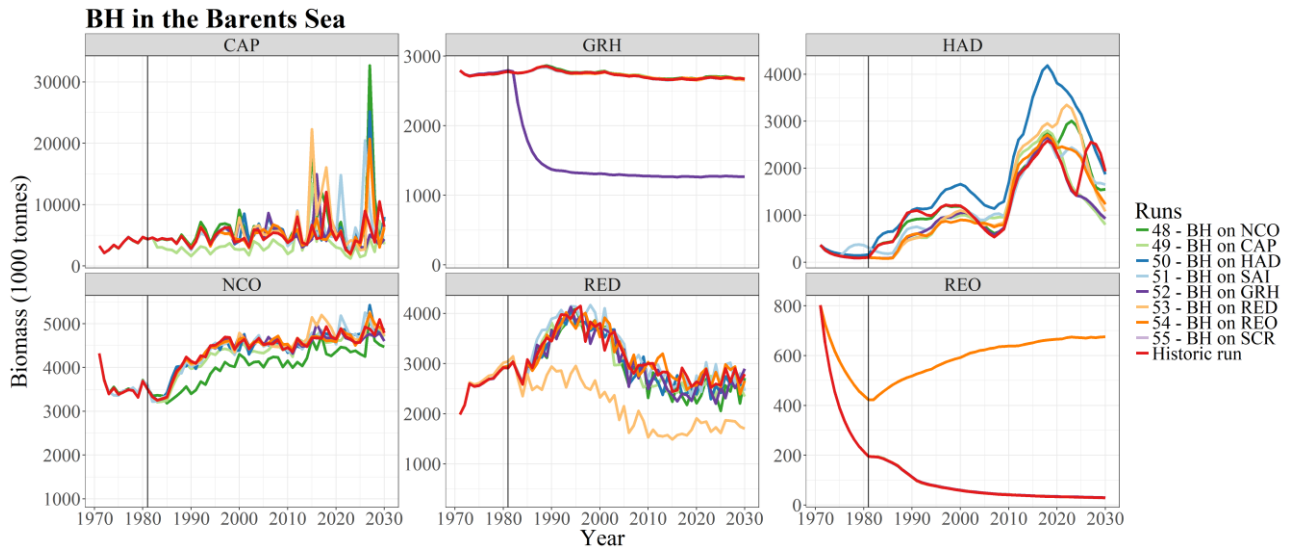


Figure 3.7 Model results imply a decreased biomass of capelin (CAP), Greenland halibut (GRH), Northeast Arctic cod (NCO) and beaked redfish (RED), while the biomasses of haddock (HAD) and golden redfish (REO) is positively affected by a balanced harvesting.

Capelin, Greenland halibut, NEA cod and beaked redfish all experienced a decrease in biomass when subjected to F_{BH} . Golden redfish was the only species in the Barents Sea with a higher F_{Histo} than the calculated F_{BH} , and experienced a severely increased biomass. Haddock appeared to be highly variable, but was mostly affected by BH on itself, resulting in a higher biomass in spite of a slightly higher fishing pressure (Table 3.1).

Although some species had a decreased biomass, the catches of all harvested species were higher under a BH regime compared to the historic fisheries (Figure 3.8), even golden redfish where a lower fishing pressure was applied.

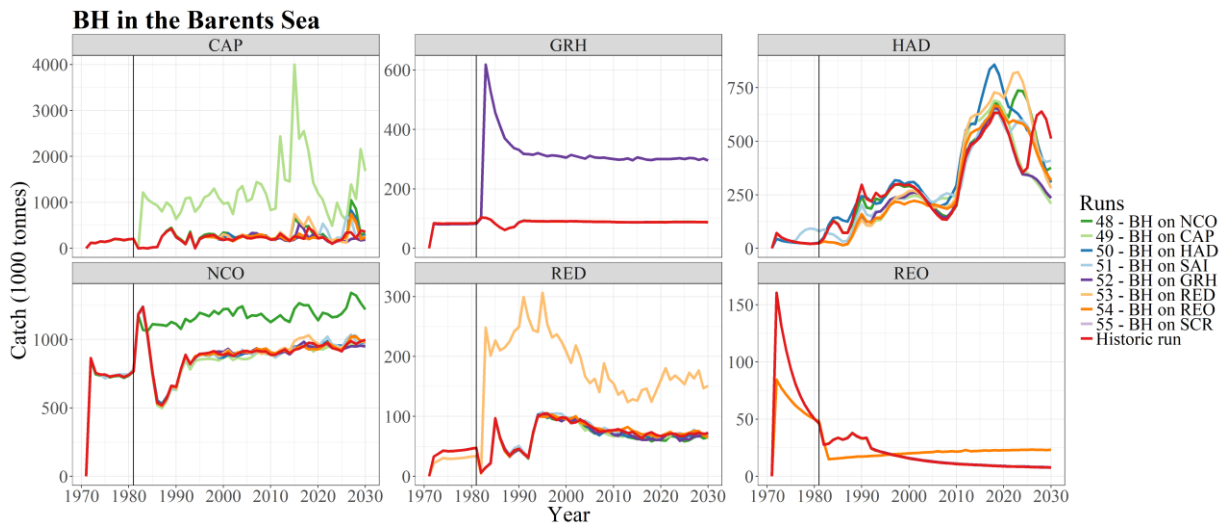


Figure 3.8 Model results imply higher catches of capelin (CAP), Greenland halibut (GRH), Northeast Arctic cod (NCO), beaked redfish (RED) and golden redfish (REO) in response to a BH fishing regime. Haddock (HAD) is highly variable with no clear run giving higher catch.

To examine the effects on age structure under a BH regime, three species were chosen as examples and shown in Figure 3.9.

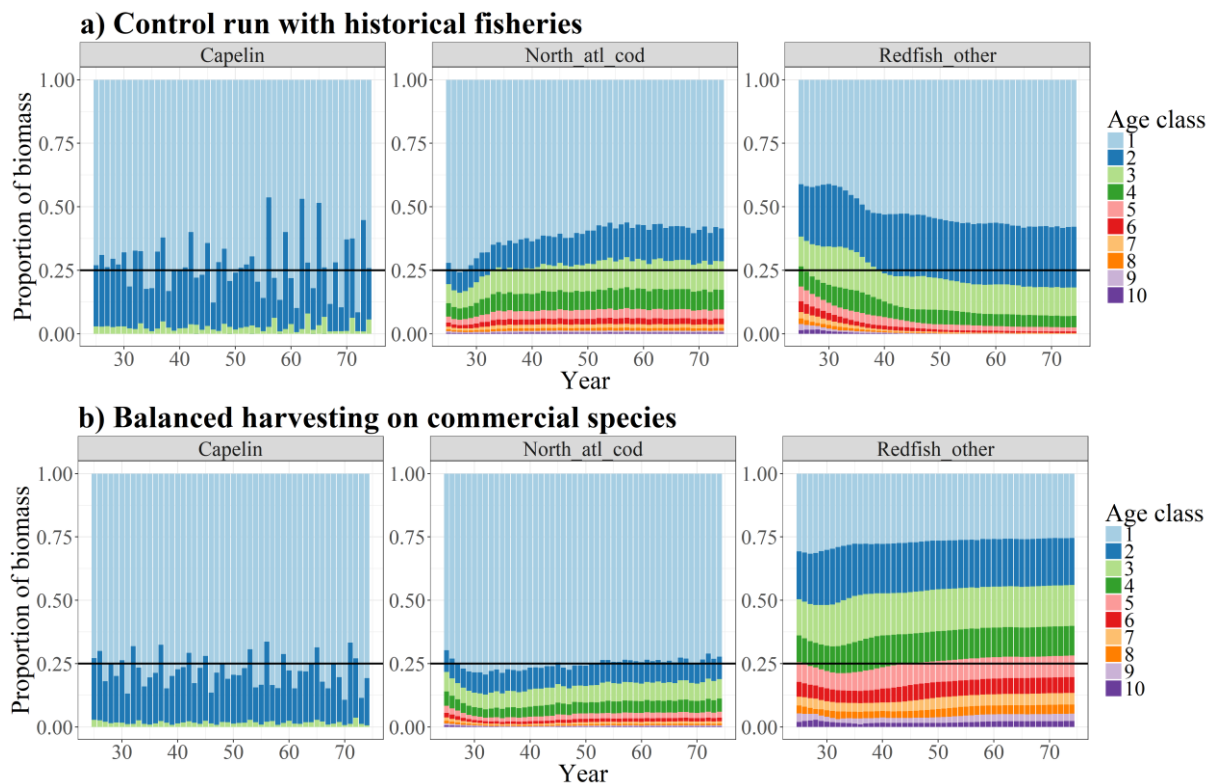


Figure 3.9 Relative composition of age classes of capelin, Northeast Arctic cod and golden redfish under historical fisheries (a), and under a balanced harvesting regime (b) through the 74 simulated years (spin-up years 1-24 excluded). Lines are added at 0.25 to make it easier for the reader to compare the plots.

The age structure of capelin was affected through a relative reduced spawning stock biomass (green – age class 3), while the opposite response was seen on the age-structure of golden redfish. These responses demonstrated the effects of a higher fishing pressure, i.e. on capelin, and a lower fishing pressure, i.e. golden redfish.

The fishing pressure on NEA cod remained rather unchanged (Table 3.1) but still had a notable effect on the relative age-structure, possibly due to alteration in selectivity. Hence, the change in age-structure for these three species highlight the effects of both a change in fishing pressure and in selectivity, due to a BH regime.

3.2 Balanced harvesting on non-commercial species

The next part of the study included harvesting of species that were considered as “non-commercial”, and not harvested in the historical control run. The calculated fishing mortalities (F_{BH}) are listed in Table 3.2:

Table 3.2. Calculated BH fishing mortalities (F_{BH}) of 25% of the productivity for all non-commercial species, including (in grey) the tested and the original F_{BH} for mesozooplankton that were not used for further simulations

Species	F_{BH}
Medium zooplankton	20.613
Medium zooplankton (x 0.50)	10.307
Medium zooplankton (x 0.25)	5.153
Medium zooplankton (x 0.15)	3.092
Gel zooplankton	0.101
Benthic filter feeders	0.877
Mesopelagic fish	0.560
Polar cod	0.107
Pelagic small	0.463
Skates rays	0.257
Long rough dab	0.481
Demersal large	0.434
Demersals other	0.398
Minke whale	0.029

3.2.1 Lower trophic levels and small fish

The effects of a BH on lower trophic level species and smaller fish are presented in Figure 3.10.

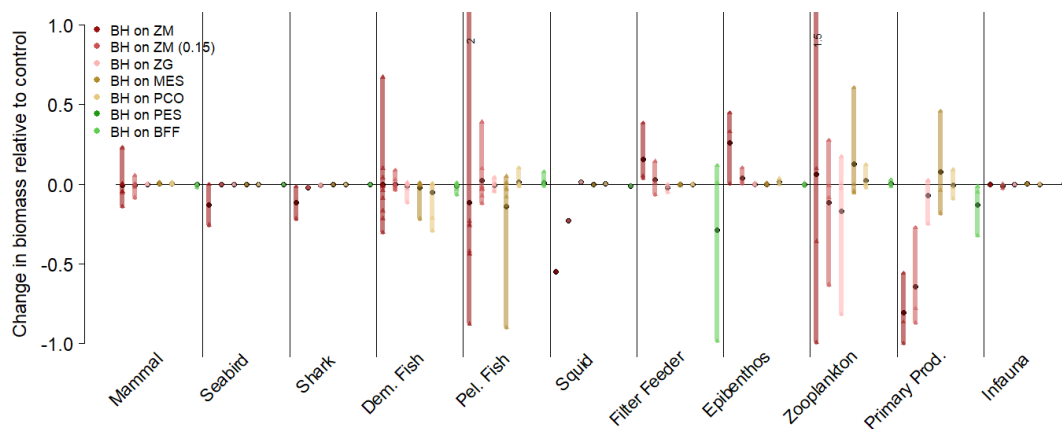


Figure 3.10 The effects on biomasses on major guilds due to balanced harvesting on non-commercial species in the Barents Sea. The bars show the relative change in biomass compared to the initial control run

The productivity of mesozooplankton was calculated to be very high, resulting in a collapse when applying a fishing mortality of 25% based on this productivity. Removing mesozooplankton from the ecosystem had profound effects on nearly all other species and functional groups (dark red lines in Figure 3.10). It was therefore decided to investigate the effects of reducing the harvest of mesozooplankton to 50 %, 25 % and 15 % of the original calculated values (one fourth of productivity).

Figure 3.11 demonstrated that reducing the mortality by 50 % still resulted in near total collapse, while reducing it to 25 % and 15 % kept the other stocks from collapsing, although the 25 % (i.e. 6.25% of its productivity) level resulted in some years of extremely low biomass. In order to simulate the impacts of a fishing pressure on mesozooplankton which had a noticeable impact on the biomass without collapsing the resource, it was decided to use the 15 % reduced fishing level (i.e. 3.25% of its productivity). The 15 % level resulted in approximate halving of the mesozooplankton biomass relative to the unfished level (Figure 3.11).

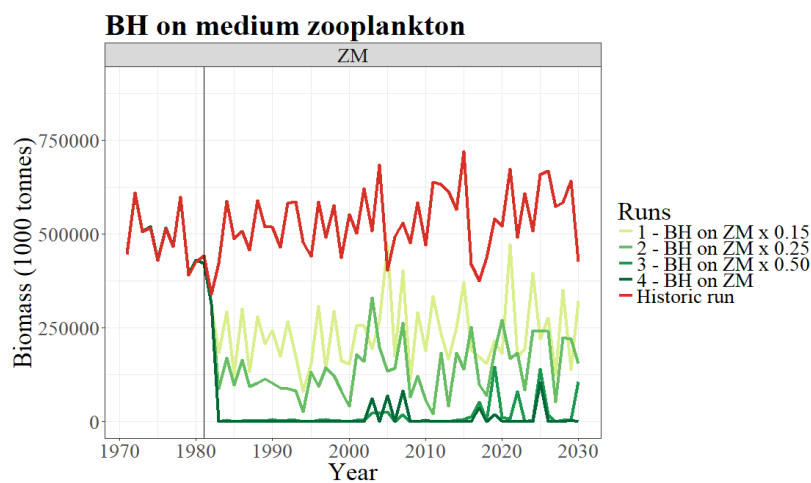


Figure 3.11 Testing reduced fishing mortalities on medium zooplankton (ZM)

When studying the biomass of the non-commercial species (Figure 3.12), both benthic filter feeders, mesopelagic fish, small pelagic fish and jellyfish were driven to near collapse when the BH fishery mortalities were applied, while polar cod and mesozooplankton (after being modified to 3.25% of its productivity, Table 3.2) seemed to tolerate it.

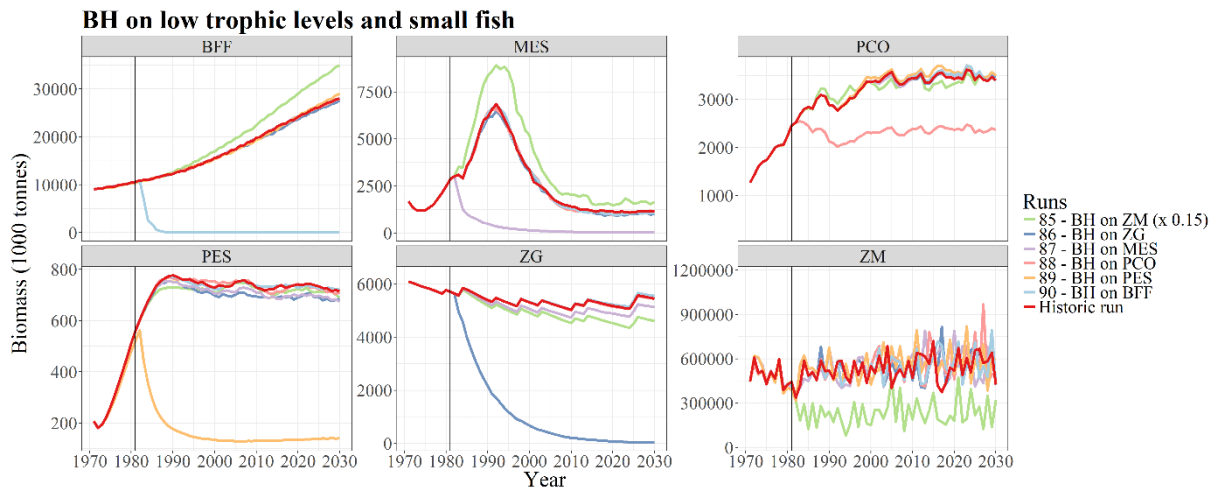


Figure 3.12 Biomass of non-commercial groups including lower trophic levels like medium zooplankton (ZM), gel zooplankton (ZG) and benthic filter feeders (BFF), in addition to smaller fish like polar cod (PCO), mesopelagic fish (MES) and a group of small pelagic fish (PES)

The catch of the non-commercial smaller species (Figure 3.13) mirrored the trends seen the biomass plots (Figure 3.12), where benthic filter feeders, mesopelagic fish, small pelagic fish and jellyfish all had an initial peak in catches when the fishing was applied, followed by a rapid exponential decrease as the stocks collapsed. The small pelagic fish did not seem to fully collapse like the others but was severely reduced both in biomass and catches. On the contrary, polar cod and mesozooplankton (after being modified) were able to tolerate the estimated fishing pressure and sustain the initial catch levels.

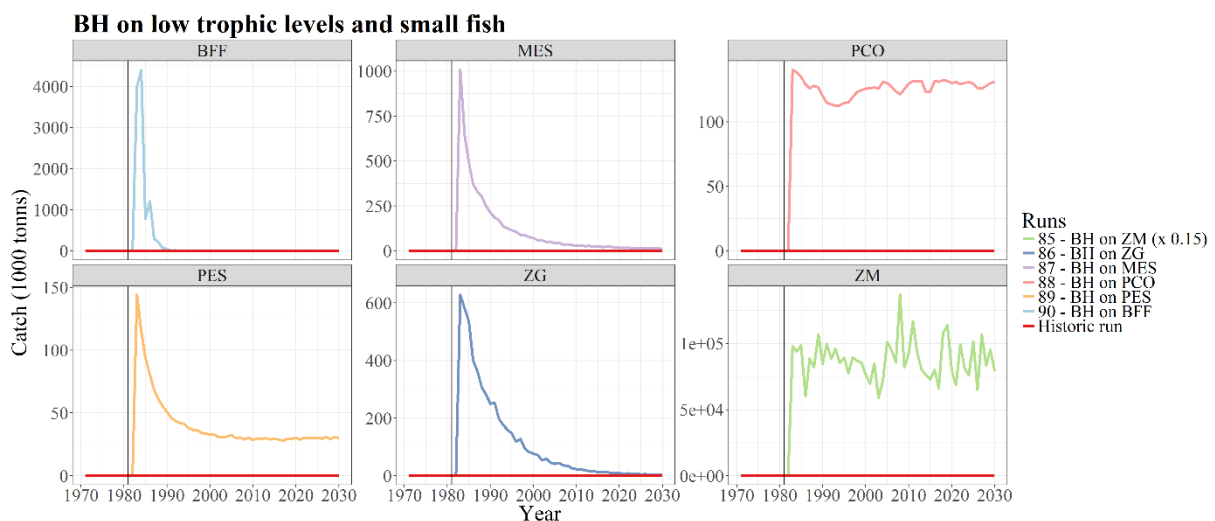


Figure 3.13 Catch of non-commercial groups including lower trophic levels like medium zooplankton (ZM), gel zooplankton (ZG) and benthic filter feeders (BFF), in addition to smaller fish like polar cod (PCO), mesopelagic fish (MES) and a group of small pelagic fish (PES)

BH on mesozooplankton had the most profound impact on other species, especially pelagic fish. Figure 3.14 show the effects of a BH regime only on mesozooplankton (green), on all commercial species (blue) and on all commercial species and mesozooplankton (light blue) along with a historic run (red). The results showed an amplified effect of harvesting on mesozooplankton when the commercial species were a BH regime (blue lines) compared to a traditional fishery (green and red lines). BH on mesozooplankton seemed to have slightly negative effects on blue whiting, herring, and mackerel (although larger effects when mackerel was subjected to BH), while having an inverse effect on mesopelagic fish.

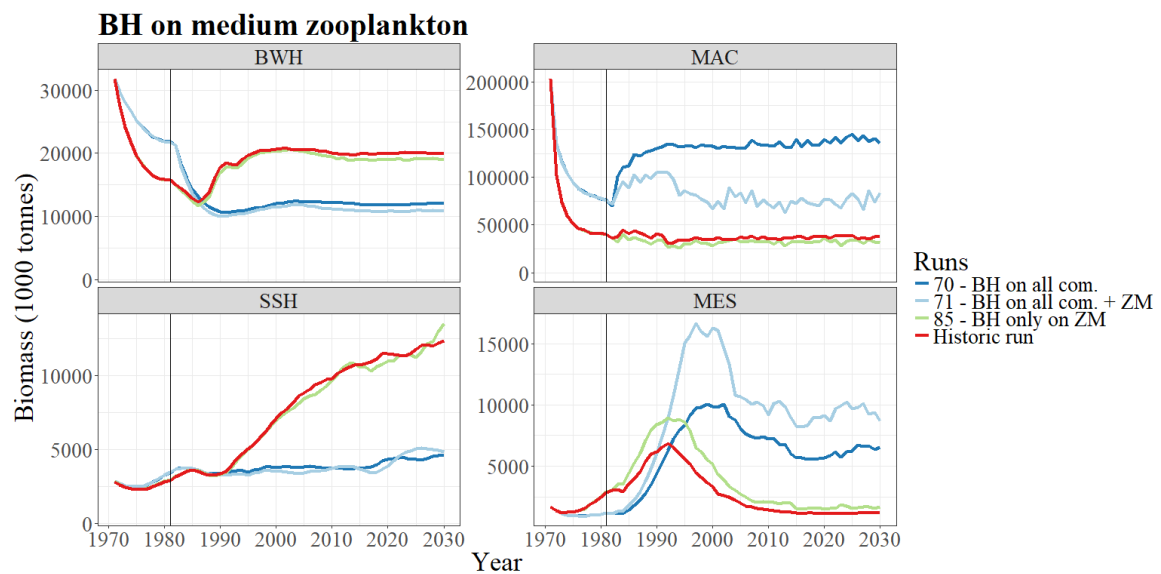


Figure 3.14 Changes in biomass through time on blue whiting (BWH), Norwegian spring Spawning herring (MAC), mackerel (MAC) and mesopelagic fish (MES) due to a balanced harvesting on medium zooplankton (ZM). The runs chosen are the historic run (red), a historic run with BH on ZM only (green), a balanced run where all commercial species are harvested (blue) and a run were all commercial species and ZM are being harvested balanced (light blue).

3.2.2 Higher trophic levels

Implementation of a BH regime also involved harvesting on higher trophic levels in proportion to productivity. Five groups of large fish and whales were selected to investigate the effects of BH on higher trophic levels. This included long rough dab, skates, minke whale and two groups of demersal fish including monkfish and wolffish (DEL) and ling and tusk (DEO). The implementation of BH on non-commercial higher trophic level species seemed to follow the same trends as on lower trophic levels, where the direct effects of the fishing pressure dominated, and most species collapsed (Figure 3.15).

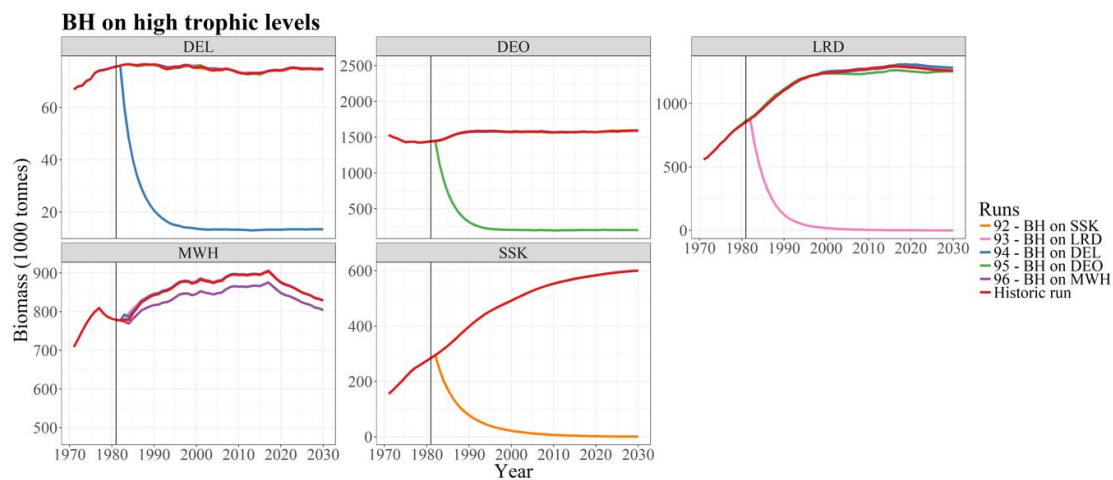


Figure 3.15 Biomass of non-commercial groups including higher trophic levels like long rough dab (LRD), skates and rays (SSK), minke whale (MWH) and two groups of large demersal fish (DEL and DEO)

Figure 3.16 show the response in catches due to the changes in biomass. All groups appeared to collapse when the BH fishery mortalities were applied, except minke whale which tolerated the fishing pressure equivalent of 25% of the productivity. Some small catches of demersal fish (DEL and DEO) were also present, despite the severely reduced biomass.

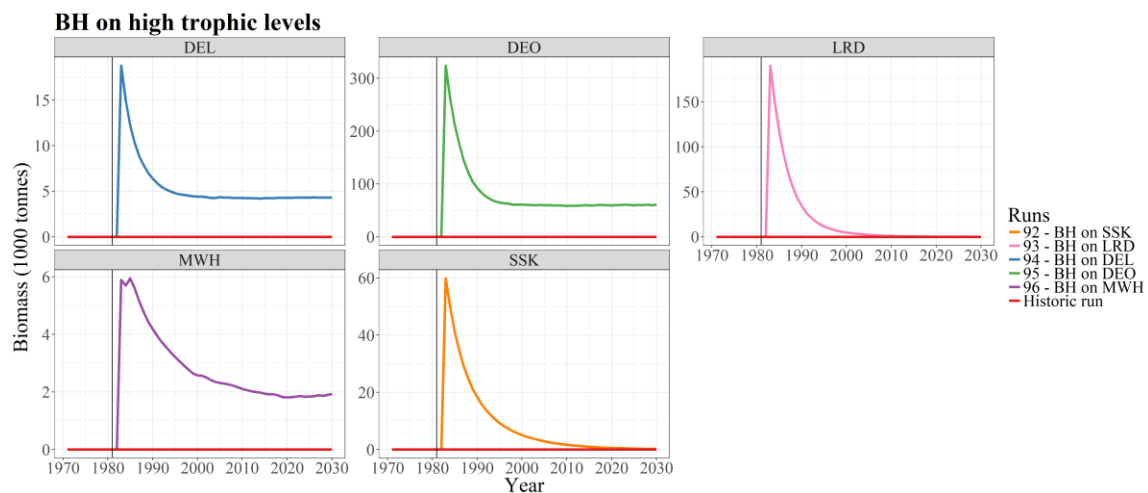


Figure 3.16 Catch of non-commercial groups including long rough dab (LRD), skates and rays (SSK), minke whale (MWH) and two groups of large demersal fish (DEL and DEO)

3.3 Effects of balanced harvesting on total yield

BH aims to provide higher yields while preserving ecosystem structure and functioning. In the following, five runs with different variations of BH was investigated in terms of providing catch. The five selected runs were:

No	Run	Description
1	Run 00	Historic run
2	Run 47	BH in the Norwegian Sea
3	Run 62	BH in the Barents Sea
4	Run 70	BH on all commercial species
5	Run 84	BH on all species

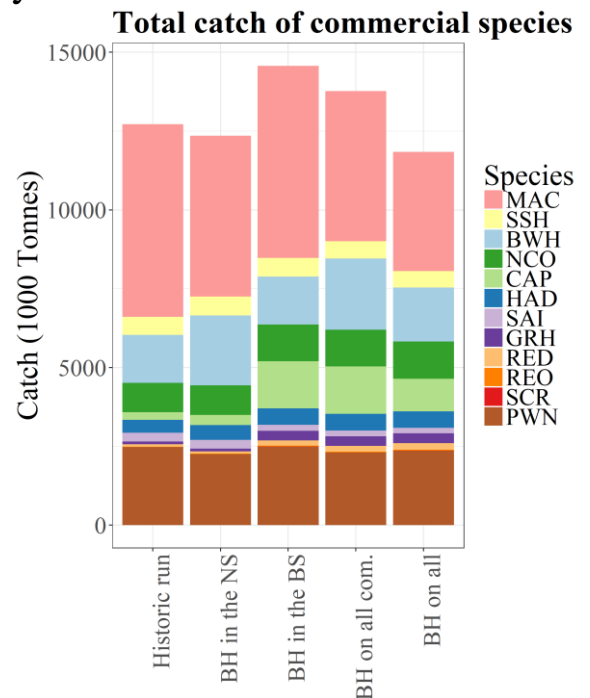


Figure 3.17 Total catch over the last 30 years of the simulations split by species. Bars represents different simulations

The average catch over last 30 years (year 2000-2030) of the simulation were used for the total catch. This was done to evaluate the long term yields of a BH regime, as some species experienced a peak in catches during first 10 years after the implementation of the BH fishery, and then stabilized on lower levels. The total catches of all commercial species are presented in Figure 3.17, and the changes in catch for the individual species are presented in Figure 3.18.

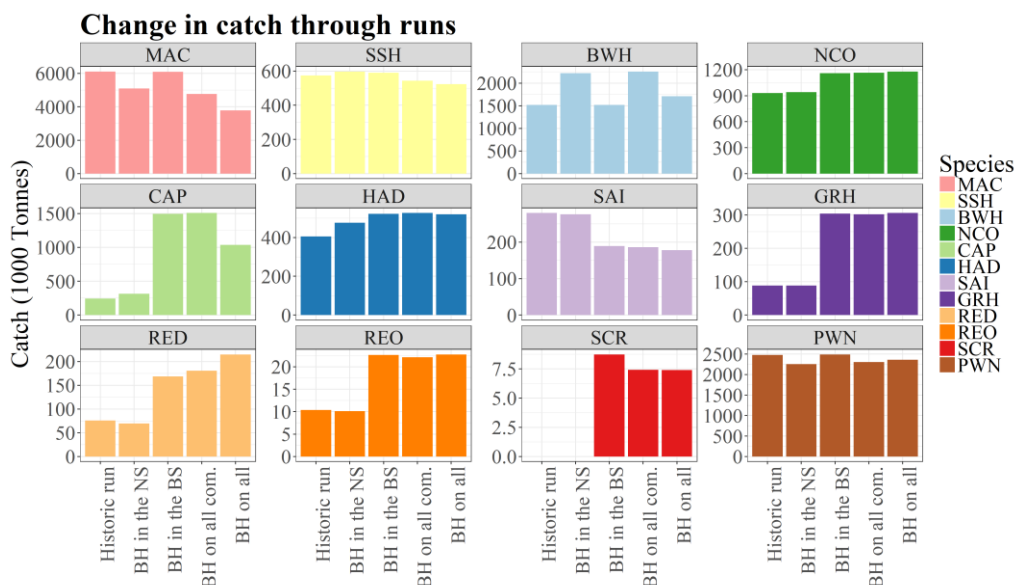


Figure 3.18 Change in total catch over the last 30 years of the simulations. Bars represents various simulations. Note the different scales of the y-axis

Figure 3.17 suggests that the highest total yield of commercial species was achieved when applying BH on commercial species in the Barents Sea (Run 62). However, when studying the individual changes in biomass for each species, it was apparent that this was mainly caused by the reduced catches of mackerel (due to the unscaled F_{BH}). Mackerel made up a substantial part of the total catch, but there were some struggles to scale the fishing pressure due to migration in and out of the model area. Consequently, mackerel was not included among the commercial species in the following plots (Figure 3.19, 3.20, 3.21 and 3.22).

The total catch of all selected species, i.e. including the non-commercial species, are presented in Figure 3.19a. The catch of the non-commercial species was lumped together when harvesting on all species (run 84). As the catches of the mesozooplankton were overwhelmingly dominating, these were excluded in Figure 3.19b for easier comparison of the remaining species. The overall trend was that the total catch increased when more species were harvested by a BH regime, mainly due to the increased catches of capelin and blue whiting. The BH on non-commercial species resulted in 63 mill tonnes extra yields, mostly mesozooplankton. However, the total catch of commercial species decreased by 1 million tonnes in this scenario.

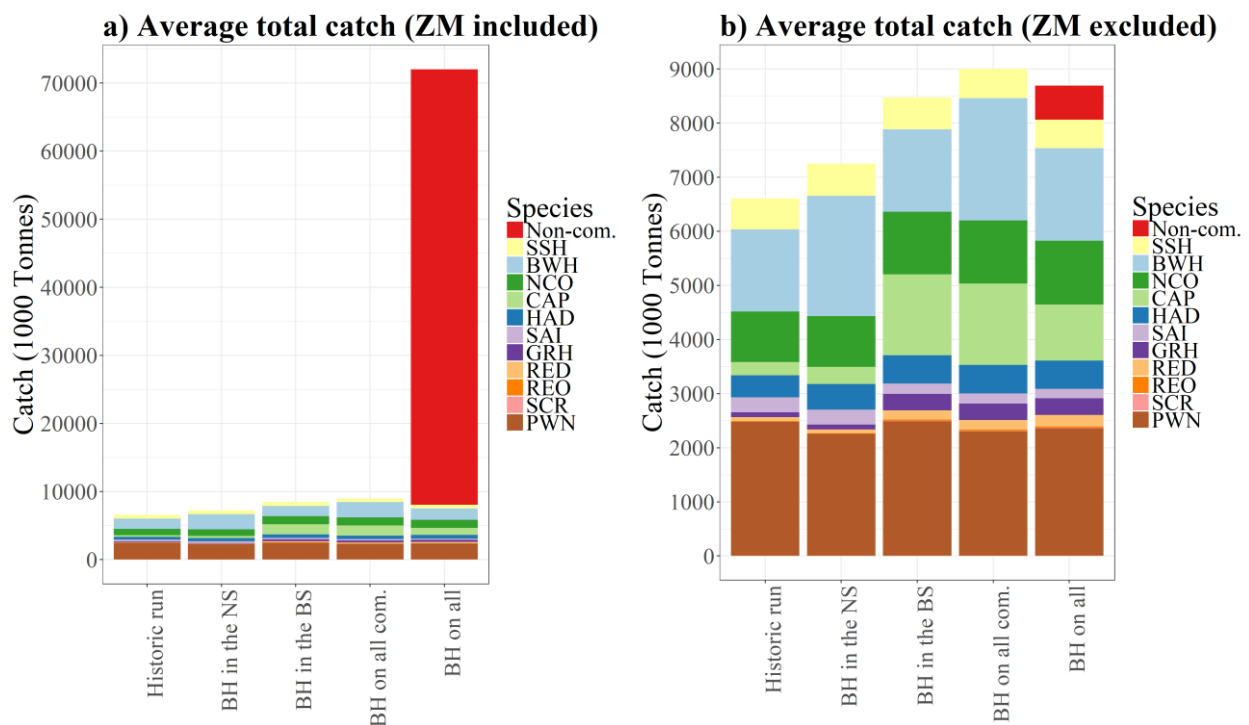


Figure 3.19 The total catches of all harvested species (excluding mackerel) in the selected runs, both with (a) and without (b) mesozooplankton (ZM). The composition of the catch is shown by colours and abbreviations

Figure 3.19b show a remaining catch of 600 000 tonnes of non-commercial species when mesozooplankton was excluded. The composition of these catches is presented in Figure 3.20, showing that most of the catch consisted of mesopelagic fish and polar cod, as well as some smaller catches of demersal fish, small pelagic fish and jellyfish.

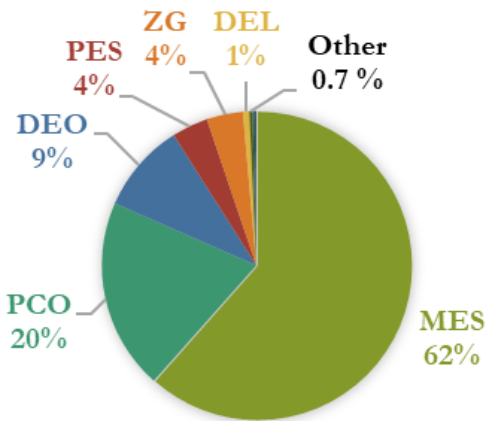


Figure 3.20 The composition of the total catch of non-commercial species (Excluding mesozooplankton)

Shifting focus from catch to standing biomass, the runs including more species being subjected to BH resulted in the lowest total biomass of commercial species (Figure 3.21). This implied that the increase in catches came at the cost of a lower overall biomass.

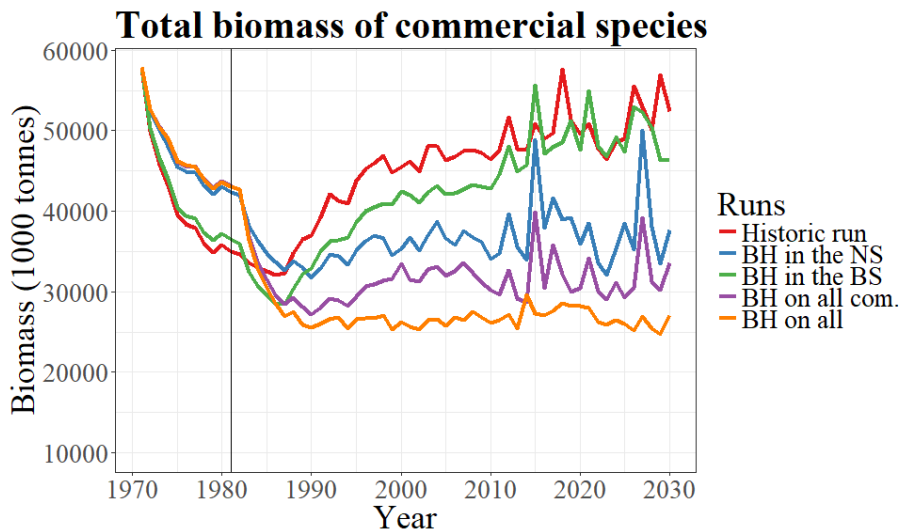


Figure 3.21 Total biomass of all commercial species through time. Prawns are not included due to the variable biomasses making visual interpretation difficult, as well as mackerel. Note that “BH on all” refers to the run where ZM is harvested i.e. corresponding to the catch in Figure 3.19a

The species most affected by the BH regime were the Greenland halibut, saithe, blue whiting and spring spawning herring, which all experienced a halving of the biomass when all components (run 84) were exposed to BH (Figure 3.22)

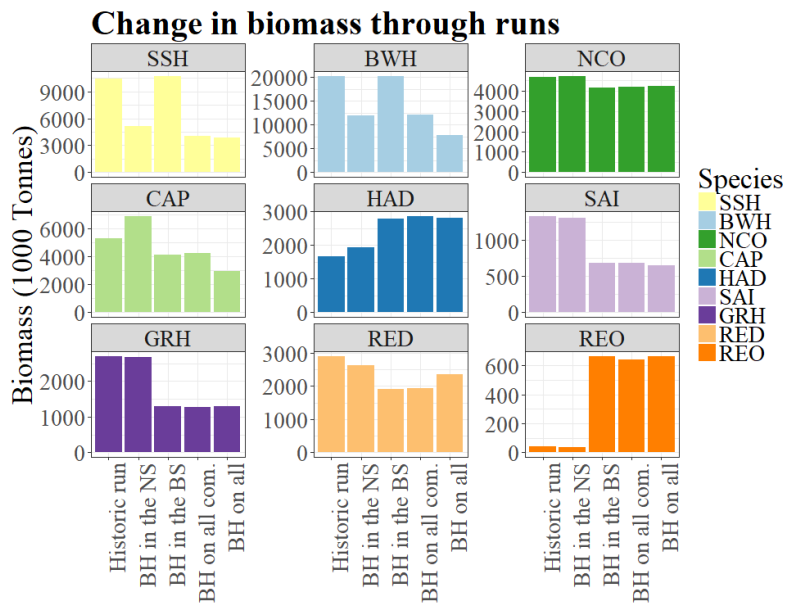


Figure 3.22 Change in total average biomass of species over the last 30 years of the simulations. Bars represents different simulations. Note the different scales of the y-axis

To investigate the relative balance of the historical fisheries included in the Atlantis model, the average catches (yields) over the whole simulated period (after the spin-up period) were plotted against the average production. Lines representing total production (red), 50 % production (yellow) and 25 % production (blue, as used in this study), were added for comparison. Figure 3.23 show that a few species, like golden redfish, haddock and saithe were harvested above the 25 % of production, while most were below the 25 % limit. Figure 3.23 also shows that the most productive species (mackerel, capelin), are the least exploited relatively.

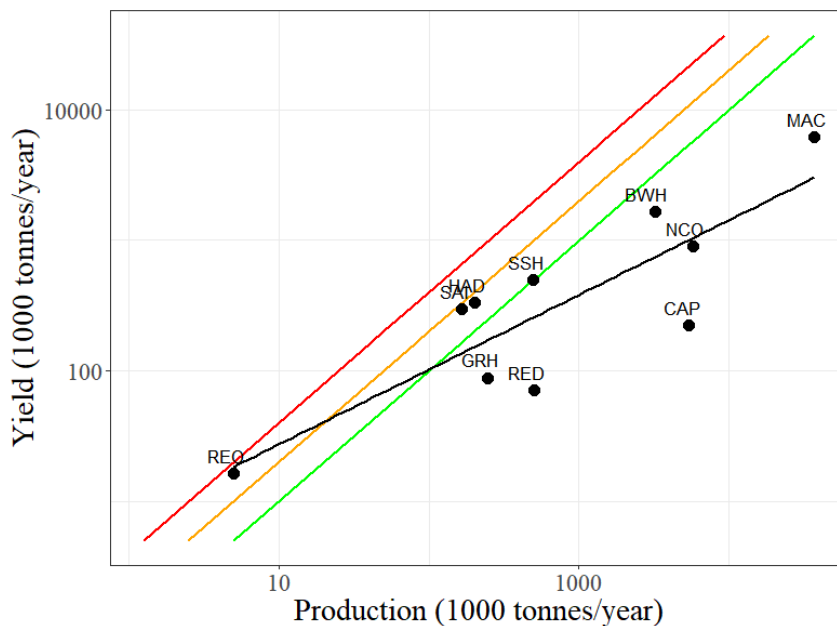


Figure 3.23 Yield relative to production for 10 of the commercially harvested stocks in the simulated control run. Red line represents the production; yellow line represents 50 % harvest of the production, while blue line represents 25 % harvest of production (i.e. what was used in this study). The axes are log scale.

4. Discussion

The aim with this study was to investigate the effects of implementing a BH regime in the Nordic and Barents Seas using a pre-parameterized Atlantis model (Hansen *et al.*, 2016). The responses to being exposed to F_{BH} were investigated for each individual species through changes in catch and biomasses, along with age composition. Some examples of how these changes affected other species than those directly subjected to F_{BH} were also given. Additionally, the average expected total catches under different degrees of BH were considered and compared to a control run.

4.1 BH effects on individual species

BH in the Norwegian Sea resulted in lower catches of mackerel (due to the unscaled F applied), and higher catches of blue whiting and herring. (Figure 3.1). The increased harvest of blue whiting caused a substantial reduction of the biomass, and this led to a major increase of mesopelagic fish (Figure 3.3). While mackerel and spring spawning herring mainly feed on zooplankton in the upper depth layers, blue whiting feeds on mesopelagic fish further down in the water column. The same response to reduced biomass of blue whiting was seen on phytoplankton (Figure 3.2), as juvenile blue whiting feeds on phytoplankton in the model.

In the Barents Sea, nearly all commercial species are currently fished close to their respective estimated MSY, with the exception of capelin, golden redfish, and Greenland halibut. Capelin is a highly variable stock in terms of recruitment and spawning stock biomass, and dies after spawning, which makes it challenging to calculate MSY. The BH on capelin suggested a higher fishing mortality (Table 3.1) resulting in 1.25 million tonnes more yield (Figure 3.22). Although the model results implied that capelin could be harvested more heavily without collapsing, the question remains whether this would be a good idea, although the dependency of cod on capelin is built into the model.

There are also uncertainties regarding MSY values for Greenland Halibut, as the assessment model is tuned only to length data, and this gives an uncertain overall biomass level and hence F in the stock assessment. Therefore, it is not clear what the current, or the long term sustainable, fishing mortalities actually are (ICES, 2015b). The calculated F_{BH} was seven times higher than the F_{Histo} , resulting in 200 000 tonnes extra yields (Figure 3.8 and 3.18) and 1 million tonnes

reduced standing stock biomass (Figure 3.7 and figure 3.22). However, as the Atlantis model is tuned to match an assessment that has known difficulties in estimating overall stock level (and hence productivity), these results should be considered uncertain.

Golden redfish has been overfished for many years (ICES, 2018) and was the only species (apart from mackerel) that actually had a lower calculated F_{BH} compared to the historic. The golden redfish represents an interesting example, as the model results indicate that fishing according to BH would result in a stock recovery, and the higher biomass would support slightly higher catches, even though the fishing pressure was less than current (Figure 3.8).

The biomass of the NEA cod was reduced when implementing a BH regime. However, the calculated F_{BH} was relatively close to F_{Histo} (compared to the changes seen for some other species). This suggests that changes in selectivity had an impact. This assumption was supported when examining the change in age composition in Figure 3.9. Stock assessment models apply a dome shaped selectivity curve with reduced pressure on the youngest and the largest fish, whereas the Atlantis model was tuned to a flat selection pattern in the historic run. The modelled selectivity on NEA cod proposed an alternative option where the youngest fish were targeted, and older fish were protected. According to Figure 3.9 this selectivity pattern caused the proportion of young fish to increase. This change in age composition could mean either that fish are targeted at a younger age and not given the chance to grow big as in traditional fishing resulting, or that larger fish being conserved (BOFFFFs) cause a higher recruitment, resulting in more young fish in age class 1.

Haddock was the only demersal species that seemed to respond strongly to harvesting on other species. Both the biomass and the catches of haddock were unstable, which is realistic to some degree as haddock has highly variable recruitment, although the model may be exaggerating this instability. The model has recruitment based on the Beverton-Holt equation (Equation 2.1), without stochastic recruitment, but even this smoothing makes it difficult to track the haddock stock.

Beaked redfish experienced a lower biomass due to a higher fishing pressure but seemed to be relatively robust to the increased F . There is a suggestion that beaked redfish may have been fished lightly following a prolonged period of recruitment failure combined with uncertainties over the SSB estimate in the assessment model, and management strategy evaluations are therefore being conducted this summer to review this (ICES, 2018).

The calculated productivities of both mesozooplankton and prawns stood out as conspicuously high compared to the other species. The calculated F_{BH} on prawns (Table 3.1) was nearly 600 times higher than the current F_{Histo} , and the fishing pressure on mesozooplankton was even higher (Table 3.2). The high fishing pressures on these two species, based on the estimated productivities, presented the opportunity to do a “validity-check” of the model, to investigate whether such derived results were realistic. In both cases the applied fishing pressures of 25% of the productivity resulted instantly in a near total collapse of the ecosystem.

The expected results of this “validity-check” were that removing mesozooplankton would have strong effects on all trophic levels (Hansen *et al.*, submitted), while removing prawns would have some effect on some large predators, but not nearly as apparent as the removal of mesozooplankton (Pantus, 2007).

Figure 3.10 showed that the effects of removing mesozooplankton were largely as expected. The zooplankton group experienced greater variations in biomass when mesozooplankton was removed, as it made room for other zooplankton to thrive, in this case the group of small zooplankton. The group of the pelagic fish experienced the same trend, as some species are highly dependent on mesozooplankton, e.g. mackerel, while some species are not, e.g. blue whiting that feeds on mesopelagic fish as well. The biomass of mesopelagic fish (Figure 3.14) was positively affected by the reduction of mesozooplankton, although mesopelagic fish feeds mainly on mesozooplankton. Studying the effects on other species uncovered that squid, jellyfish, small pelagic fish and blue whiting all prey on mesopelagic fish, and all these experienced a decrease in biomass. This top-down effect, along with the fact that mesopelagic fish can switch to small zooplankton for food as these became more abundant (bottom-up), were probably the reasons to the large increase of mesopelagic fish.

Prawns are known to be a challenge in several Atlantis models, and in the NoBa model the biomass of prawns is too high (Cecilie Hansen pers. Comm). The high biomass of prawns cause the predators to eat more prawn than they are expected to do, and thereby becoming highly dependent on prawns. This over-dependency was demonstrated when applying the high F_{BH} on prawns, causing many higher trophic level species to collapse (Figure 3.6). The BH fishing pressure was set at 25% of the prawn productivity, so we would not have expected this to have such a great effect on other species, and this identified a logic problem within the model.

The BH of most species categorized as “non-commercial” in the model (either unexploited or lightly exploited) resulted in an initial peak in catches (Figure 3.13 and 3.16), followed by a collapse. The uniform collapse of the non-commercial species suggested that either the methodology used to calculate the F_{BH} did not work for these species (although the approach was the same as for the commercial species), or that the model had been parameterized and tuned for these species in such a way that the model could not tolerate any additional fishing mortality.

The latter seems most plausible as the non-commercial species generally have higher natural mortality applied than those commercially harvested. This is likely a result of the model development focussing primarily on the dynamics of the commercially most important species. The two species that did tolerate the additional fishing pressure were minke whale and polar cod. Polar cod is mainly distributed along the ice front and is rather separated from predators compared to other small fish, while minke whale also have few predators (Cecilie Hansen pers. Comm). This, in an addition to both of them having low calculated F_{BH} , could be the reason why these two were the only non-commercial species that tolerated the BH. However, it suggests that as currently parameterized, the NoBa Atlantis model is limited to examine the effects of changing fishing patterns on currently exploited species.

To summarize, all species in this study experienced a lower biomass when subjected to the BH regime (apart from mackerel, haddock, golden redfish) due to the higher fishing mortalities (F_{BH}) that were the outcome when setting them equal to 25% of the estimated productivity. A principle of BH is that the fishing mortality (to some degree) substitutes the natural predation mortality, as more catch means less predation. Still, the “moderate fishing mortality” is not well defined in BH, and if the gains from reduced predation are less than the loss from increased F, then the biomass will go down.

4.2 BH effects on total catch

The total catch figures represented averages from the 30 last years of the simulations (year 2000-2030), to avoid unsustainable short-term spikes in catches during the first years after implementation, as well as any other short-term dynamics imposed by the change of fishing regime. As there were some struggles to scale the fishing pressure on mackerel due to migration in and out of the model area, mackerel were only shown in Figure 3.17 and 3.18 along with the other commercial species and excluded from further examinations.

When mesozooplankton was included in the balanced harvest, it completely dominated the total catch (Figure 3.19a). Although the fishing pressure on mesozooplankton was subsequently reduced to 15 % of the original 25% of productivity (thus only 3.75% of the estimated productivity), the harvest still caused a 50 % decrease of the biomass (Figure 3.11), which seems highly unlikely with such a small extraction ratio. Considering that the current quota is set to 165 000 tonnes (Fiskeridirektoratet, 2016) of a stock with a standing biomass of 30 million tonnes, and an annual production of 290 million tonnes, a harvest of 63 million tonnes (Figure 3.19) would not be feasible according to the model. The extra yields of mesozooplankton came at the cost of nearly halving the standing biomass of commercial species (Figure 3.21), and the lower the biomass gets, the more it increases the risk of recruitment overfishing.

In Figure 3.19b the catch of mesozooplankton was excluded from the non-commercial group for better comparison of the remaining species. When comparing the control run with combined runs of balanced harvesting on multiple species, the results indicated that more species being subjected to BH resulted in higher catches. Studying the composition of these catches it was apparent that the main increase came from capelin and blue whiting (and to some degree Greenland halibut and beaked redfish). The remaining catch of the non-commercial species made a rather small contribution of 600 000 tonnes (compared to the 63 mill tonnes when mesozooplankton was included).

The simulations presented here suggest that the gains from BH in the Barents and Norwegian Sea are rather limited according to the current model. However, given the instances of unrealistic behaviour for some key components of the ecosystem, these results should be treated with caution. In particular, it should be emphasized that if the non-commercial species had been tuned in the model to allow an additional fishing pressure, the additional catches of non-

commercial species would probably have been considerably higher. Long rough dab for instance, are abundant in the Barents Sea and would most likely tolerate a fishery. Such additional catches are not realized in these simulations, probably due to the parameterization issues discussed above.

The results of this study indicate that implementing a full BH regime in the Norwegian and Barents Seas at the level of fishing pressure used here would cause more damage to the already exploited species in the form of reduced biomass (Figure 3.21), than would be gained in total yields. Even if this conclusion is a result of the applied model, this may not be because BH is a bad idea.

The figure in Howell *et al.* (2016) based on an Ecopath model from Skaret & Pitcher (2016) demonstrated that the harvesting of the Norwegian and Barents were more balanced than most marine systems (Kolding *et al.*, 2016), in terms of harvesting many of the targeted stocks proportionally to their productivity (Figure 4.1). Although not as apparent, Figure 3.23 showed a similar trend when plotting the yields of commercial species in the Atlantis model against their production. This implies that any extra yields would be expected to come largely from currently unexploited or underexploited species – and the current model configuration was not able to assess this.

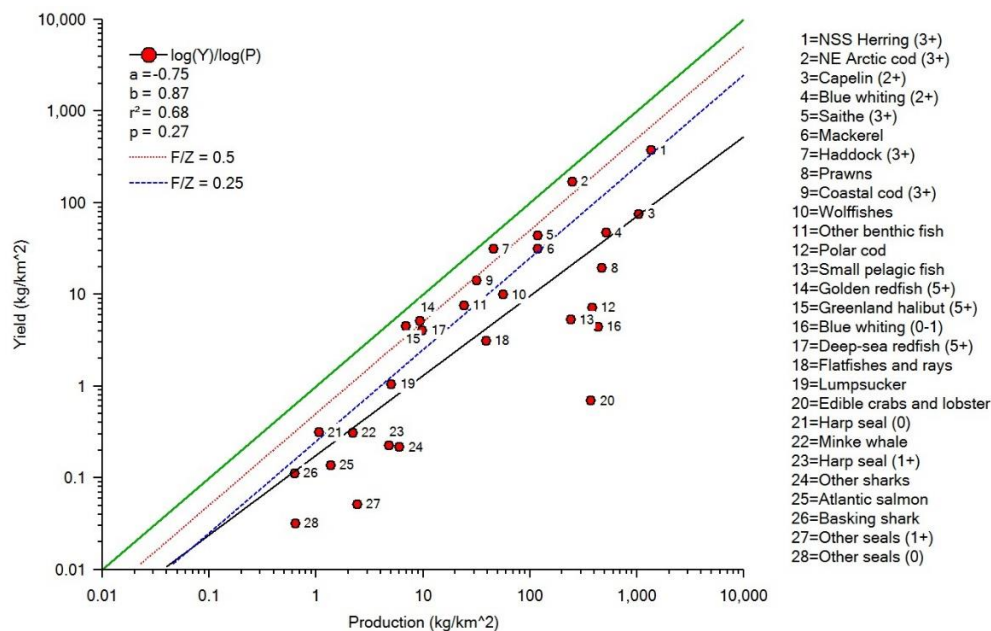


Figure 4.1 Harvest relative to production for the 28 stocks and groups harvested in the Norwegian/Barents Sea extracted from an Ecopath model for the two seas. Figure from Howell *et al.* (2016) based on data from Skaret & Pitcher (2016)

4.3 Assessment of uncertainties

Even though the Atlantis model is able to capture a wide range of the variability inherent in the ecosystems, increased uncertainty follows such increased complexity (Howell *et al.*, 2016). Several assumptions and “guesstimates” must be made to accommodate the lack of knowledge about processes and absence of relevant data. Generality, precision and realism are three desired features in a model, but unfortunately complex models, with a multitude of parameters, are generally not able to attain all three, and therefore de-emphasizes one quality to optimize the other two (Olsen *et al.*, 2016). Being an end-to-end model, Atlantis is designed to provide an overall context, with focus on generality and realism, but clearly some weaknesses and inexplicabilities have been discovered in this study.

It should be emphasized that nearly all fisheries models, whether single-species, multispecies, or ecosystem-based, contain assumptions that could be considered as uncertainties. In order to evaluate how the functional and trophic structure of an ecosystem is going to change in response to fishing, these assumptions are almost unavoidable. Still, the results should always be interpreted through the lens of the model's underlying assumptions (Andersen *et al.*, 2016).

End-to-end models, like Atlantis, are considered best-suited for providing strategic advice, while models of less complexity are more appropriate when tactical advice is needed, because they provide estimates of the uncertainty of their predictions. Atlantis is not intended to replace traditional stock assessments, setting quotas or other purposes where precision is the most crucial part (NOAA, 2014). In an extensive skill assessment survey performed by Olsen *et al.* in 2016 on the Atlantis model covering Northeast US (NEUS), they concluded that we can generally “*rely on ecosystem-models to guide us in strategic decision-making on large-scale socio-ecological questions*” (Olsen *et al.*, 2016).

The Atlantis model has been repeatedly tested and modified to represent the “reality” to the best of our ability. The NoBa model was tuned to survey data and stock assessment which has rich observational data for multiple species, derived from semi-annual trawl surveys as well as other monitoring programs. Data regarding each functional group were assembled from the published literature over many years from a variety of studies and experts on the different groups were also contacted to evaluate the rates and equations being used for each functional group (Hansen *et al.*, 2016).

But in the end, all models are simplifications of the reality aimed to simulate and predict natural processes, given our present understanding. Although Atlantis is considered one of the most advanced ecosystem models in the world, it will never be able to capture all aspects of the real ocean. Or as the statistician Georg Box said;

“Essentially, all models are wrong, but some are useful” (Box, 1976).

4.4 Future work and suggestions for improvements

The non-commercial functional groups receive a lot less attention during the parameterization and tuning of the model, both because the focus is on the “important” commercial species, and because there is less information on the non-commercial groups (Cecilie Hansen pers. Comm). The first step in improving these results would be to do a comprehensive re-tuning of the non-commercial species to allow for an additional fishing mortality without the instant collapse.

The method for calculating production and productivity levels for invertebrates should also be reviewed, as both prawns and mesozooplankton experienced unrealistically high F_{BH} . The calculations for invertebrates was done differently than for vertebrates, as invertebrates are gathered into biomass pools with a given production rate, that had to be multiplied by the total area. In addition, the code for how the productivity is calculated for printing within the model should be investigated, as it may very well be that it is the way that it is printed and not the methods that causes the problems.

The migration of mackerel outside the model domain caused the fishing pressure to be lower than the stock could potentially support. By scaling up the fishing mortalities, the results could be considerably improved as mackerel makes up a large proportion of the total catches. An additional update of the code and parameter files would lead to better results on saithe which were troubled in the current update, as well as inducing the historical fisheries on snow crab that were excluded from the first runs.

Expanding the study to investigate various types of BH would be very interesting. There is an ongoing debate on whether BH should be done in proportion to **productivity** (as in this study) or in proportion to **production** (Heath *et al.*, 2017). The key difference between the two is that production is density dependent, while productivity is density independent, with the following equations:

$$\text{Production (BH1):} \quad F(x) = c \cdot P(x) = c \cdot g(x) \cdot B(x) \quad (4.1)$$

$$\text{Productivity (BH2):} \quad F(x) = c \cdot \frac{P(x)}{B(x)} = c \cdot g(x) \quad (4.2)$$

For both equations, the fishing mortality F , on species x , is determined by the magnitude of the exploitation constant, c , and the species-specific production, $P(x)$, calculated from the biomass, B , and growth, g . Since fishing in proportion to BH1 is density dependent, it tends to be zero as the biomass is low, and thereby protects species with low biomass from collapse. Fishing according to BH2 on the other hand, is not sensitive to current biomass, and thereby allow for species to be exploited to extinction, as also the results of the examination shows.

Heath *et al.*, (2017) argued that since BH is an ecosystem approach to fishing with an explicit aim of maintaining the species richness of marine ecosystems, the density-dependent fishing mortality in BH1 is the best method for achieving this and therefore what they would recommend. It would be interesting to investigate how a BH based on production (BH1) would compare to a BH based on productivity (BH2), and to explore whether the assumptions behind BH1 protection species from extinction would be validated.

5. Conclusions

Through scenarios with varying fishing pressure and fishing patterns in proportion to calculated productivities, we investigated the interaction effects of harvesting different components in the ecosystem. The conclusions from these simulations were that:

- Model results indicate that a BH regime would result in higher total yields, mainly from lower trophic level species.
- However, the extra yields were mainly from capelin and mesopelagic fish (when zooplankton was excluded) and came at the expense of reducing the standing stock biomass of commercial species to nearly half.
- The model results suggest that implementing a BH regime in the Norwegian and Barents Seas at the level of fishing pressure used here, would cause more harm to the already exploited species in terms of reduced biomass, than would be gained in total yields.
- The Norwegian fisheries already scores high on BH aspects, with fishing levels close to MSY. The reason why this study showed that there were not much to be gained from a BH regime, may therefore be because they are pretty close to one already.
- Several weaknesses, inconsistent dependencies, and somewhat inexplicable results were identified in the current model. In addition, the methods used in this study to calculate productivity levels were not straight forward, and a balanced fishing pattern on all components of the system has never been applied before in this model.

The presented examination of applying the strategic harvesting pattern of Balanced harvest, using an Atlantis model, is the first time this approach has been tried. As usual, when endeavouring into uncharted and untested territory, we end up with more questions than answers.

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Appendix 1 – Productivity and fishing mortality

Table A.1

Getting production estimates from the Atlantis model proved to be far more difficult than anticipated. Several attempts were made, as this output had never been tried before.

Attempt 1: Calculate the productivity based on growth and recruitment

Each age class of all age-structured species has a defined proportion of sexually mature adults. To account for the recruitment as a part of the production, the total recruitment biomass of every stock was multiplied with the amount of mature adults.

The problem with this approach was getting information on the migrating species, especially recruitment. To access the recruitment of the migrating species, the model had to be run in debug-mode, and even this caused problems with unrealistic numbers for some of the species.

After discussing this, it became clear that the production should be treated as the production "coming into" a given size (or age) class, not the production "going out" of the size or age class. Hence reproduction should be counted as recruits coming into the system rather than eggs produced by parent, and the information on recruitment was no longer needed

Attempt 2: Calculate the productivity based on the natural mortality rate

Since BH aims to mimic the natural mortality in the ecosystem, an alternative approach was to harvest in proportion to the natural mortality rate. This was done by gathering information on mortality rates from the parameter files and estimate the average predation mortalities of each functional group throughout the modelled years.

The problem with this method was that the predation mortality is printed before considering the available prey biomass. This resulted in higher mortality rates than what was actually applied, reflecting what the predators wanted to eat and not what they truly did eat. This became obvious when examining the calculated fishing mortalities as several species had unrealistically high values (Table A.2).

Table A.2 Calculated fishing mortalities based on natural mortality

Specie	Mean
<i>Mackerel</i>	7,06E+22 ≈1
<i>Blue_whiting</i>	0,15
<i>Norwegian_ssh</i>	3,18 ≈1
<i>Haddock</i>	35,86 ≈1
<i>Saithe</i>	10,45 ≈1
<i>North_atl_cod</i>	0,97
<i>Capelin</i>	0,56
<i>Green_halibut</i>	0,05
<i>Redfish</i>	1,33 ≈1
<i>Redfish_other</i>	0,27
<i>Snow_crab</i>	0,02
<i>Prawns</i>	7,86E+15 ≈1

While searching for a better way to do this, some runs were done using this method. However, due to the uncertainties, these are not included in the results.

Attempt 3: Calculate the productivity based natural mortality through individuals lost

By tracking the number of fish in a cohort from year to year, it should be possible to estimate the mortality through back-calculations. The same principle is used in virtual population analysis where the number of individuals lost each year is used for reconstructing historical fish abundance (Table A.3)

Table A.3 Example illustrating how the back-calculations could be done

Age:	Year:						
	1990	1991	1992	1993	1994	1995	1996
1	1000						
2		550					
3	-450		350				
4		-200		200			
5			-150		100		
6				-100		30	
7					-70		0

-30

The problem with this method was that even though most vertebrates are separated in 10 age classes, these age classes does not represent the same number of years (for example capelin which has age classes represented by 1 compared to golden redfish represented by 4 years). This would have required running the model in debug mode again and tracking the printing in the outputs

Attempt 4: Calculate productivity based on the consumption of predators.

By calculating the amount of prey eaten from the diet outputs, it could be possible to estimate the mortality of prey species. Unfortunately, since these are given as a proportion and not a total, one would have to use the mortality rates and then experience the same problems as in attempt 2.

Attempt 5: Calculate the productivity based on the mass balance formulation

By rearranging the mass balance formulation and calculate the productivity based on the amount of biomass produced each year.

Russel’s mass balance formulation (Russell, 1931):

$$B_{t+1} = B_t + R_t + G_t - M_t - C_t$$

The mass balance formulation states that the biomass next year (B_{t+1}) depends on the biomass this year (B_t), recruitment (R_t), growth (G_t), mortality (M_t) and catches (C_t). This can be rearranged to:

$$R_t + G_t = B_{t+1} - B_t + M_t + C_t$$

The two sources of increase, growth (G_t) and recruitment (R_t), equals the production (P_t). By rearranging the formulation to have these two on one side, we get an equation that represents the production, and this can then be divided by B_t to get a rate.

$$\frac{P_t}{B_t} = \frac{B_{t+1} - B_t + M_t + C_t}{B_t}$$

Since the aim is to balance over sizes as well as species, the equation can be modified to include age classes and get the production of each age class for all vertebrate groups.

$$\frac{P}{B} = \frac{(B_{a+1,t+1} - B_{a,t}) + M_{a,t} + C_{a,t}}{B_{a,t}}$$

This gives the surplus production produced each year by each age class, and thereby the amount of living material generated through biomass, catch and mortality estimates. This attempt was abandoned when a better approach (the one used) was uncovered.

Attempt 6: Calculate production based on the MSY

Since MSY is related to the carrying capacity, and hence productivity, a fishery harvested with rates based on MYS would be considered to be fairly balanced.

This was based on earlier work on balanced harvesting using an Atlantis model in Garcia *et al.* (2012) done by Elizabeth Fulton (pers. comm). Unlike the ones above, this approach was never attempted, but kept as a possible back-up strategy should the others fail.

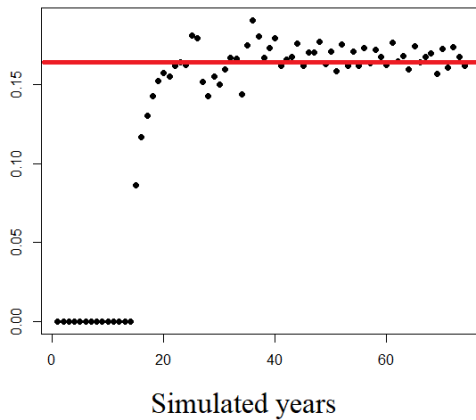
Table A.4

Table show the difference in *p/b*-ratio and fishing mortality (*F*) when excluding age class 1. All species, except blue whiting, long rough dab, mackerel, pelagic large and snow crab, were reduced. Last column shows change in percentage when moving from all age classes included to age class 1 excluded

Species	Age class 1 <u>included</u>		Age class 1 <u>excluded</u>		Difference %
	<i>P/B</i> -ratio	<i>F_{BH}</i>	<i>P/B</i> -ratio	<i>F_{BH}</i>	
<i>Bearded seal</i>	0.21	0.052	0.09	0.023	-56 %
<i>Blue whiting</i>	2.04	0.510	2.24	0.561	10 %
<i>Capelin</i>	5.19	1.298	1.43	0.357	-73 %
<i>Demersal large</i>	1.77	0.443	1.74	0.436	-2 %
<i>Demersal other</i>	1.99	0.498	1.59	0.398	-20 %
<i>Fin whale</i>	0.39	0.097	0.09	0.022	-78 %
<i>Flatfish other</i>	0.73	0.183	0.59	0.148	-19 %
<i>Greenland halibut</i>	1.02	0.256	0.91	0.228	-11 %
<i>Haddock</i>	1.32	0.330	1.13	0.283	-15 %
<i>Harp seal</i>	0.19	0.046	0.07	0.019	-60 %
<i>Hooded seal</i>	0.70	0.174	0.56	0.140	-20 %
<i>Humpback whale</i>	0.40	0.099	0.12	0.031	-69 %
<i>Killer whale</i>	0.28	0.070	0.19	0.047	-33 %
<i>Long rough dab</i>	1.83	0.458	1.92	0.479	5 %
<i>Mackerel</i>	2.03	0.509	4.57	1.121	125 %
<i>Mesopelagic fish</i>	8.63	2.158	2.16	0.540	-75 %
<i>Minke whale</i>	0.46	0.116	0.11	0.029	-75 %
<i>Northeast Arctic cod</i>	3.28	0.820	1.23	0.308	-62 %
<i>Norwegian S.S herring</i>	0.80	0.199	0.67	0.169	-16 %
<i>Pelagic large</i>	2.05	0.512	2.19	0.549	7 %
<i>Pelagic small</i>	2.32	0.580	1.86	0.464	-20 %
<i>Polar bear</i>	0.09	0.023	0.01	0.001	-100 %
<i>Polar cod</i>	2.14	0.534	0.43	0.107	-80 %
<i>Redfish</i>	0.90	0.226	0.46	0.115	-49 %
<i>Redfish other</i>	0.39	0.097	0.27	0.066	-32 %
<i>Ring seal</i>	0.21	0.052	0.07	0.018	-66 %
<i>Saithe</i>	1.40	0.350	1.35	0.337	-4 %
<i>Sea bird arctic</i>	0.39	0.097	0.17	0.042	-57 %
<i>Sea bird boreal</i>	0.25	0.062	0.05	0.014	-78 %
<i>Sharks other</i>	0.78	0.194	0.47	0.119	-39 %
<i>Skates rays</i>	1.13	0.281	1.03	0.257	-9 %
<i>Snow crab</i>	1.28	0.320	1.47	0.367	15 %
<i>Sperm whale</i>	0.17	0.042	0.05	0.014	-68 %

Figure A.1

a) Historic run



b) BH on mackerel

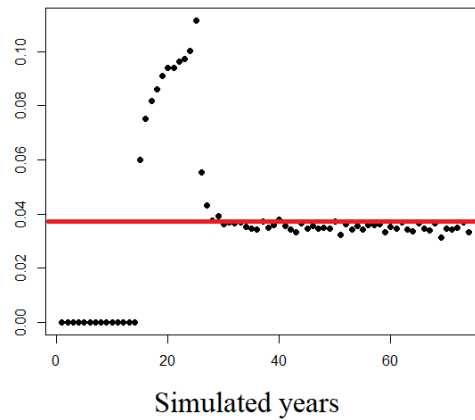


Figure A.1 Realized fishing pressure on mackerel in the historic run (a) is around 0.16, while the fishing pressure in the BH regime (b) is around 0.04.

Figure A.1 show the realised fishing pressure on mackerel for (a) the historic run and (b) the balanced harvest run by plotting catch/biomass. This demonstrates how the migration affected the catches, as the original fishing pressure in the historic run was 3.452, while the fishing pressure in the balanced run was set to 1.121. Hence;

$$F_{\text{Histo}}: 3.452 \div 0.16 = 21.6$$

$$F_{\text{BH}}: 1.121 \div 0.04 = 28$$

It was attempted to scale up the fishing mortality by a factor of 28 and thereafter by a factor of 21.6. However, as the on mackerel was calculated as very high, this resulted in a collapse both times. Due to the time frame on this thesis, no further attempts were made, and mackerel was fished with an unscaled fishing mortality.

Appendix 2 – Selectivity

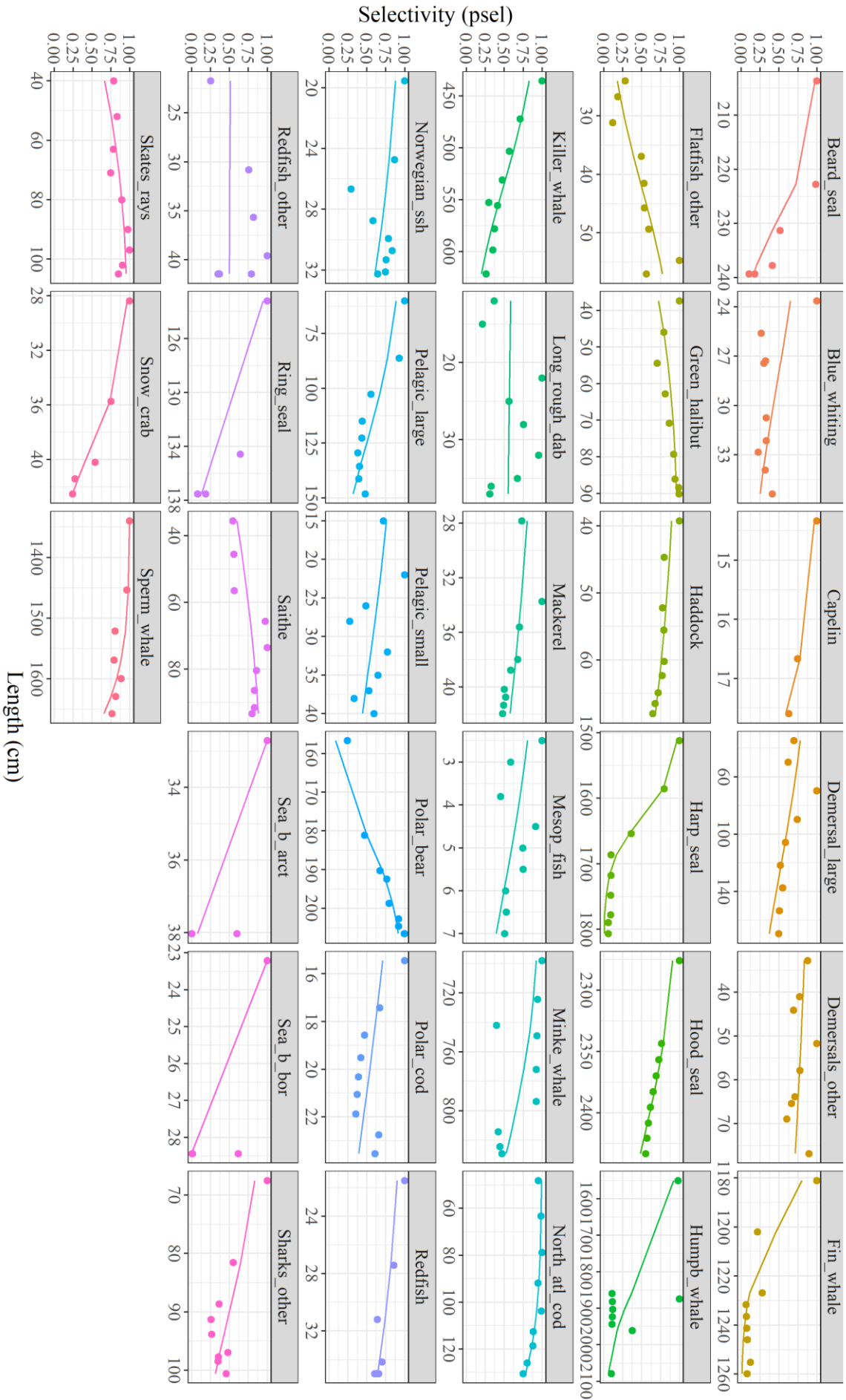
Table A.5

Harvested species connected to model fishing fleets with associated selection curve parameters for all age structured groups.

No	Species	Fishing fleet	lsm [cm]	selb
1	<i>Norwegian S.S herring</i>	pseineSSH	46	-0.0790
2	<i>Blue whiting</i>	pseineBWH	28	-0.1476
3	<i>Mackerel</i>	pseineMAC	36	-0.1212
4	<i>Capelin</i>	pseineCAP	18	-0.9317
5	<i>Northeast Arctic cod</i>	dtrawlNCO	157	-0.0489
6	<i>Haddock</i>	dtrawlHAD	84	-0.0485
7	<i>Saithe</i>	dtrawlSAI	21	0.0282
8	<i>Greenland halibut</i>	dtrawlGRH	15	0.0436
9	<i>Prawns</i>	dtrawlPWN		
10	<i>Redfish</i>	dlineNCO	40	-0.1208
11	<i>Snow crab</i>	dlineHAD	39	-0.3187
12	<i>Redfish other</i>	dlineSAI	41	-0.0035
13	<i>Zooplankton medium + zooplankton gel</i>	dlineGRH		
14	<i>Mesopelagic fish</i>	dseineNCO	6	-0.4145
15	<i>Polar cod</i>	dseineHAD	21	-0.1636
16	<i>Pelagic small</i>	dseineSAI	36	-0.0551
17	<i>Benthic filter feeders</i>	dseineGRH		
18	<i>Skates rays</i>	netNCO	21	0.0364
19	<i>Long rough dab</i>	netHAD	77	-0.0053
20	<i>Demersal large</i>	netSAI	130	-0.0134
21	<i>Demersals other</i>	netGRH	133	-0.0164
26	<i>Minke whale</i>	cullMWH	835	-0.0186

Figure A.2

Selectivity curves for all age-structured groups (excluding age class 1). The points represents the mean productivity level at a given size scaled from 0-1, and the line represents the best fitted curve using non-linear square regression.



Appendix 3 – Simulations

Table A.6

Complete list of all runs done in this study. The i.d. of the simulation is given along with the description and whether age class 1 was included or excluded when calculating fishing mortalities and setting selection curves. Runs marked with grey are runs not used for analysis in this study.

No	Run	Description	Age class
1	run_000	No fishing	All
2	run_00	Historic run (1981 – 2031)	All
3	run_01	BH on MAC	All
4	run_02	BH on SSH	All
5	run_03	BH on BWH	All
6	run_04	BH on MAC	All
7	run_05	BH on SSH	All
8	run_06	BH on BWH	All
9	run_07	BH on MAC + SSH	All
10	run_08	BH on SSH + BWH	All
11	run_09	BH on BWH + MAC	All
12	run_10	BH on MAC, SSH, BWH (Norwegian Sea)	All
13	run_11	BH on NCO	All
14	run_12	BH on CAP	All
15	run_13	BH on HAD	All
16	run_14	BH on SAI	All
17	run_15	BH on GRH	All
18	run_16	BH on RED	All
19	run_17	BH on REO	All
20	run_18	BH on SCR	All
21	run_39	BH on PWN	All
22	run_19	BH on NCO	All
23	run_20	BH on CAP	All
24	run_21	BH on HAD	All
25	run_22	BH on SAI	All
26	run_23	BH on GRH	All
27	run_24	BH on RED	All
28	run_25	BH on REO	All
29	run_26	BH on SCR	All
30	run_27	BH on NCO + PWN	-
31	run_28	BH on NCO + CAP	All
32	run_29	BH on NCO, CAP + HAD	All
33	run_39	BH on NCO, CAP, HAD + SAI	All
34	run_31	BH on NCO, CAP, HAD, SAI + GRH	All
35	run_32	BH on NCO, CAP, HAD, SAI, GRH + RED	All
36	run_33	BH on NCO, CAP, HAD, SAI, GRH, RED + REO	All
37	run_34	BH on NCO, CAP, HAD, SAI, GRH, RED, REO + SCR	All
38	run_35	BH on NCO, CAP, HAD, SAI, GRH, RED, REO, SCR + PWN (Barents Sea)	All
39	run_36	BH on Barents Sea + MAC	All
40	run_37	BH on Barents Sea + SSH	All
41	run_38	BH on Barents Sea + BWH	All

42	run_40	BH on Barents + Norwegian Sea	All
43	run_41	BH on MAC	Minus ycl 1
44	run_42	BH on SSH	Minus ycl 1
45	run_43	BH on BWH	Minus ycl 1
46	run_44	BH on MAC + SSH	Minus ycl 1
47	run_45	BH on SSH + BWH	Minus ycl 1
48	run_46	BH on BWH + MAC	Minus ycl 1
49	run_47	BH on MAC, SSH, BWH (Norwegian Sea)	Minus ycl 1
50	run_48	BH on NCO	Minus ycl 1
51	run_49	BH on CAP	Minus ycl 1
52	run_50	BH on HAD	Minus ycl 1
53	run_51	BH on SAI	Minus ycl 1
54	run_52	BH on GRH	Minus ycl 1
55	run_53	BH on RED	Minus ycl 1
56	run_54	BH on REO	Minus ycl 1
57	run_55	BH on SCR	Minus ycl 1
58	run_19	BH on PWN	Minus ycl 1
59	run_56	BH on NCO + CAP	Minus ycl 1
60	run_57	BH on NCO, CAP + HAD	Minus ycl 1
61	run_58	BH on NCO, CAP, HAD + SAI	Minus ycl 1
62	run_59	BH on NCO, CAP, HAD, SAI + GRH	Minus ycl 1
63	run_60	BH on NCO, CAP, HAD, SAI, GRH + RED	Minus ycl 1
64	run_61	BH on NCO, CAP, HAD, SAI, GRH, RED + REO	Minus ycl 1
65	run_62	BH on NCO, CAP, HAD, SAI, GRH, RED, REO + SCR	Minus ycl 1
66	run_63	BH on NCO, CAP, HAD, SAI, GRH, RED, REO, SCR + PWN (Barents Sea)	Minus ycl 1
67	run_64+p	BH on Barents Sea + MAC	Minus ycl 1
68	run_64	BH on Barents Sea (- PWN) + MAC	Minus ycl 1
69	run_65+p	BH on Barents Sea + SSH	Minus ycl 1
70	run_65	BH on Barents Sea (- PWN) + SSH	Minus ycl 1
71	run_66+p	BH on Barents Sea + BWH	Minus ycl 1
72	run_66	BH on Barents Sea (- PWN) + BWH	Minus ycl 1
73	run_67	BH on Barents Sea + MAC+SSH (-PWN)	Minus ycl 1
74	run_68	BH on Barents Sea + SSH+BWH (-PWN)	Minus ycl 1
75	run_69	BH on Barents Sea + BWH+MAC (-PWN)	Minus ycl 1
76	run_70+p	BH on all commercial species (Norwegian and Barents Sea)	Minus ycl 1
77	run_70	BH on all commercial species (Norwegian and Barents Sea) -PWN	Minus ycl 1
78	run_71	BH on all commercial + ZM (x 0.15)	Minus ycl 1
79	run_72	BH on all commercial + ZG	Minus ycl 1
80	run_73	BH on all commercial + MES	Minus ycl 1
81	run_74	BH on all commercial + PCO	Minus ycl 1
82	run_75	BH on all commercial + PES	Minus ycl 1
83	run_76	BH on all commercial + BFF	Minus ycl 1
84	run_77	BH on all commercial + ZM (x 0.15), ZG, MES, PCO, PES, BFF	Minus ycl 1
85	run_78	BH on all commercial + SSK	Minus ycl 1
86	run_79	BH on all commercial + LRD	Minus ycl 1
87	run_80	BH on all commercial + DEL	-
88	run_81	BH on all commercial + DEO	-
89	run_82	BH on all commercial + MWH	Minus ycl 1
90	run_83	BH on all commercial + SSK, LRD, DEL, DEO, MWH	Minus ycl 1
91	run_84	BH on all species (NB! PWN excluded, ZM x 0.15)	Minus ycl 1
92	run_85	BH on ZM	-
93	run_85_5	BH on ZM (x 0.50)	-
94	run_85_2	BH on ZM (x 0.25)	-

95	run_85_1	BH on ZM (x 0.15)	-
96	run_86	BH on ZG	-
97	run_87	BH on MES	Minus ycl 1
98	run_88	BH on PCO	Minus ycl 1
99	run_89	BH on PES	Minus ycl 1
100	run_90	BH on BFF	Minus ycl 1
101	run_91	BH on ZM (x 0.15), ZG, MES, PCO, PES, BFF	Minus ycl 1
102	run_92	BH on SSK	Minus ycl 1
103	run_93	BH on LRD	Minus ycl 1
104	run_94	BH on DEL	Minus ycl 1
105	run_95	BH on DEO	Minus ycl 1
106	run_96	BH on MWH	Minus ycl 1
107	run_97	BH on SSK, LRD, DEL, DEO, MWH	Minus ycl 1
108	run_98	BH on ZM(x0.15), ZG, MES, PCO, PES, BFF, SSK, LRD, DEL, DEO, MWH	Minus ycl 1