Cod spawning in the Borgundfjord Marine Protected Area

Estimation of the spawning stock biomass, and an evaluation of the Marine Protected Area and the fluctuations in the spawning stock biomass from year to year.

Master thesis in Fisheries Biology and Management

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ABSTRACT

The Norwegian coastal cod population north of 62°N declined in the years from 1997 to 2005 and has since remained low. The Borgundfjord has since 2009 served as an extractive Marine Protected Area (MPA) for protecting the coastal cod, as it is an important spawning ground for this threatened population. This implies that the area is closed for commercial harvesting and net fishing during the spawning season lasting from 1 March to 31 May. Recreational angling is however permitted.

The Institute of Marine Research has from 2012 to 2019, with an exception in 2014, performed weekly net hauls during the spawning season. In this study I have analysed the egg data from these hauls, with the aim of estimating the annual spawning stock biomass (SSB) in the area, and in that way evaluate if the introduction of the MPA has had any effect on the coastal cod population in Borgundfjord. The biomass was estimated to be around 200 – 400 tonnes, where the highest SSB was estimated for 2013 (~ 590 tonnes), but the 95 % confidence interval showed a great uncertainty. Year 2017 had the lowest estimated SSB at approximately 145 tonnes. I have investigated whether other factors than an actual change in SSB could have caused the fluctuations in the egg-based SSB estimates from year to year, including factors like sea currents, hydrography and condition of the female cod. None of these factors seem to explain the fluctuations in SSB. The results suggest that there neither has been an increase in the SSB nor a drop in the mortality as consequence of the MPA implementation. Because of this, it is argued that the MPA has not had the desired effect of protecting the coastal cod.

This study describes a standardized way of estimating the spawning stock biomass of cod within a Marine Protected Area, using data from net hauls, egg genetics, hydrography and commercial cod landings. This standardized way could be applied to other MPAs where it is desired to estimate the SSB.

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1 Introduction

1.1 Background

Cod (*Gadus morhua*) is a well-known species with different stocks spread throughout the Atlantic Ocean. In the northeast part of the ocean, hence in Norwegian waters north of 62°N, it is typically distinguished between two types of cod. These are called the Norwegian coastal cod (NC cod) and the Northeast Arctic cod (NEA cod), where the latter one often is called *skrei* in Norwegian. While the stock of NEA cod potentially is the largest cod stock in the world (Bogstad, 2017; Hylen, Nakken, & Nedreaas, 2008; ICES, 2019b) and currently in a sustainable condition, the coastal cod is in a more vulnerable state and struggling (Aglen et al., 2016; ICES, 2019b; Johansen et al., 2017; Wennevik, Jørstad, Dahle, & Fevolden, 2008). Coastal cod are likely to consist of several subpopulations on a regional/local scale along the coast, with differences in life history traits like growth, mortality, migration and time of maturation (Dahle et al., 2018; Knutsen, Olsen, & Espeland, 2017; Olsen et al., 2010; Wennevik et al., 2008; Yaragina, Aglen, & Sokolov, 2011). All along the coast of Norway there are cases where local populations of NC cod have declined, and in some places almost disappeared. The overall stock of NC cod populations north of 62°N had a decline in the years from 1997 to 2005, and has since remained relatively low (ICES, 2019a). Different regulation measures have been taken, e.g., in fjords like the Borgundfjord and the Oslofjord in an attempt to rebuild the local stocks (Johansen et al., 2017; Lorentzen, 2018).

The Borgundfjord is an important spawning area for the threatened NC cod stock. As a measure to protect this stock, the fjord has since 2009 served as an extractive Marine Protected Area (MPA), implying that net fishing and commercial harvest are not allowed during the cod's spawning season lasting from 1 March – 31 May. Recreational fishing is however allowed. The Institute of Marine Research (IMR) has, in cooperation with Runde Environmental Centre, conducted sampling of cod eggs in the spawning seasons from 2012 to 2019, with an exception in 2014. Based on the data gathered, this study will give an estimate of the spawning stock biomass (SSB) each year.

1.2 Biological factors of the cod in Borgundfjord - differences between NC cod and NEA cod.

1.2.1 Cod in general

Cod (*Gadus morhua*) is a benthopelagic species which is widely distributed in the North Atlantic. It is mainly known as a demersal fish, but may appear in open waters to spawn and feed (Bogstad, 2017; Devine, 2017). At the eastern part of the Atlantic ocean you find it from the Bay of Biscay in south, to Iceland, Greenland, Svalbard and Novaja Semlja in the north (Moen & Svensen, 2004). Along the North American coast, it is distributed from Cape Hatteras in the south to Ungava Bay in the north (Devine, 2017; FAO, 2019). The cod is typically found in habitats ranging from open oceans, to fjords and over coastal banks (Berg & Albert, 2003), and its vertically distribution ranges from the shore and down to 600 metres (Berg & Albert, 2003; Moen & Svensen, 2014). Cod prefer to spawn at temperatures between 4°C to 7°C (González-Irusta & Wright, 2016; Yaragina et al., 2011), and is a so-called batch spawner, meaning one individual spawn multiple times during the spawning season. The spawning period for a cod population lasts from two to two and a half months (Kjesbu, 1989). When it comes to food, cod eats almost everything that can fit its mouth, making it an important predator in the food web (Myers & Worm, 2005).

For Norway, cod is one of the most important fish species, both culturally and commercially. Norway exported 181 000 tonnes of cod in 2019, for a total value of 10.1 billion NOK (Norges sjømatråd, 2020). It is prepared and sold in either dried, salted, frozen, fresh or smoked form (Moen & Svensen, 2014).

1.2.2 Life history: Northeast Arctic cod versus Norwegian coastal cod

NC cod and NEA cod are close to identical when it comes to morphology and appearance. NEA cod could be slimmer and NC cod could have a clear, seaweed-like red tone in their skin, but this is not a waterproof way to separate them. The traditional way to separate them has been to use the otolith structure (Rollefsen, 1933), which is done by looking at morphological differences in shape of the otolith and the growth zones within. They can also be separated by the number of vertebrae (Rollefsen, 1934). In a general manner, NC cod matures earlier and grows faster than the NEA cod (Aglen, 2017), as they experience different environmental conditions. Despite the similarities, their life histories are quite different.

The Northeast Arctic cod spends most of its life in the Barents Sea, and has its nursery and feeding grounds there (Hylen et al., 2008). In January to March, it migrates great distances southwards along the coast of Norway to various spawning locations (Hylen et al., 2008; Michalsen, Johansen, Subbey, & Beck, 2014; Opdal & Jørgensen, 2015). Eggs and larvae from these spawning grounds floats in the upper water columns, and follow the sea currents back up north to the Barents Sea, where they become juveniles and settle to the bottom (Opdal & Jørgensen, 2015).

The coastal cod, on the other hand, lives a more stationary life. It is mainly found in the coastal areas and in the fjords along the Norwegian coast, and has limited seasonal migrations (Michalsen et al., 2014). The spawning takes place from late January to May, and the eggs and larvae are retained in the fjord and coastal areas close to the spawning site, before they during the following summer settle as juveniles at shallow waters in nursery areas (Olsen et al., 2010). The abundance of NCC increases from south to north (Berg & Albert, 2003), and approximately 75 % of coastal cod is found north of 67°N (Aglen, 2017).

The coastal cod can again be divided into two components: fjord-cod and bank-cod or migrating coastal cod. Fjord-cod may stay in the fjord the whole year through, although Jakobsen (1987) showed that up to 10 % of cod tagged in one fjord might be recaptured in the neighbour fjord. There have also been studies showing that the coastal cod rarely migrate more than 16 kilometres as the median distance (Aglen et al., 2020). Bank-cod is more mobile and can migrate to fish banks and shelf edge to eat. It does however use the fjords or areas closer to the coast for spawning (Havforskningsinstituttet, 2009).

1.2.3 Population structure of NC cod and mixing between NC cod and NEA cod

Traditionally, ICES has treated the NC cod as two separate management units: north and south of 62°N. Coastal cod are however likely to consist of several separate populations spawning in the different fjords along the coast of Norway (Berg et al., 2016; Olsen et al., 2010; Wennevik et al., 2008), as eggs and larvae are retained in the fjord and the gene flow between populations is low. Genetic studies have revealed different populations of NCC. Both studies using the *Pan* I locus and studies using microsatellite markers have been used, where differences in genetic structures have been found among distinct fjords and different offshore areas (Fevolden & Pogson, 1997; Sarvas & Fevolden, 2005b). You could even have different populations within the same fjord, as there was found two stocks of NC cod in Ullsfjord in Northern Norway showing differences in growth rates and length at maturity (Berg & Pedersen, 2001). Hence, there is not one big NCC population, but many smaller, regional/local ones. These are genetically different from each other, where it seems to be differences in both age and length at maturation and growth (Dahle et al., 2018; Knutsen et al., 2017).

Little is known about hybridisation between NC cod and NEA cod, even though there has been conducted some research. NC cod typically possess the homozygous Pan I^{AA} genotype, while NEA cod typically possess the Pan I^{BB} genotype. There are however areas in Northern Norway with cod that possess intermediate allele frequencies (Sarvas & Fevolden, 2005a), meaning that the alleles of coastal cod is not necessarily mainly the Pan I^{AA} genotype. Dahle et al. (2018) suggested that the observed population genetic structure of NC cod along the coast was partly due to mixing of genes between NC cod and NEA cod, where there were most introgression (gene flow between the stocks) in the north and least in the south. This indicates that there could happen hybridization between NEA cod and NC cod.

1.2.4 Differences in egg buoyancy

As the end station of the NEA cod larvae in Borgundfjord is the Barents Sea and the end station of NC cod larvae is the coastal are or the fjords, there has to be something at early life history differentiating the two stocks. It has long been discussed that the NC cod eggs are heavier than the NEA cod eggs, hence that the neutral buoyancy of NC cod eggs is lower in the water column compared to NEA cod eggs (Kjesbu, Kryvi, Sundby, & Solemdal, 1992; Knutsen et al., 2017; Myksvoll, Sundby, Ådlandsvik, & Vikebø, 2011; Stenevik, Sundby, & Agnalt, 2008). This makes the NC cod eggs less exposed to currents made by the wind, and the eggs and larvae are retained in the fjord. The eggs of NEA cod, with a neutral buoyancy higher in the water column, would be transported northwards to the Barents Sea by the Norwegian coastal current. However, there has also been shown a great overlap in the buoyancy between NC cod and NEA cod eggs (Jung et al., 2012), indicating that there is no difference. The egg specific gravity does however change with time, and the reduction in egg specific gravity among NEA cod eggs could be higher than among NC cod eggs in the later stages of development. Hence, NEA cod eggs could be more prone to currents in the latest stages of development.

1.3 The different management needs of the NC cod and the NEA cod

When populations that do not have the same abundance or resilience against exploitation is under the same management regime, then will the least abundant population often be exposed to overfishing (Dahle et al., 2018; Ruzzante et al., 1998). NC cod are less abundant than NEA cod, and the two cod types are thus in the need of different management regimes. ICES has since 2001 given advice for rebuilding of the NC cod stock, and from the years from 2004 to 2011 they even recommended zero catch of NC cod (ICES, 2019b; Johansen et al., 2017). Zero catch is anyhow difficult and unrealistic to achieve, as the NEA cod and NC cod some places have an overlapping distribution during the spawning season, even though NC cod tend to spawn closer to shore and in shallower water (Olsen et al., 2010). The overlapping distribution and the close to identical morphology, does that the NC cod and NEA cod often get caught in the same fisheries. It has been estimated that as much as 60-70% of the yearly catch of NC cod happens when NEA cod is the main target (ICES, 2015, as cited by Johansen et al., 2017), but this number may range from 0 to almost 100. Therefore, to achieve zero catch of NC cod, as advised by ICES, all coastal fisheries where NC cod are caught as bycatch must be closed. This has been considered impractical, and other measures has been put into action instead. This includes reducing the total annual quota of NC cod and making regulations to minimize the catch and bycatch of NC cod (ICES, 2019b; Johansen et al., 2017). The main idea behind the regulations was to shift the fishing pressure from coastal cod over to the Northeast Arctic cod, and in that way make most of the total landings to consist of NEA cod (Aglen, 2017; ICES, 2019b).

The spawning grounds for NEA cod, where most of the overlapping occurs, are in the areas around Lofoten (coastal areas between 67 and 69°N) (Michalsen et al., 2014; Olsen et al., 2010). There are anyhow also important spawning grounds further south where Borgundfjord is placed, at the Møre region at approximately 62 to 63°N (Bergstad, Jørgensen, & Dragesund, 1987; Johansen et al., 2017; Olsen et al., 2010). It is important that places like these have regulations to reduce the bycatch of NC cod, as they have a high fraction of NC cod.

1.4 What has caused the NC cod to struggle?

Overfishing is thought to have significantly impacted the NC cod stock, and there are several examples of different cod stocks that have suffered due to overfishing (Engelhard et al., 2014; Hilborn et al., 2003; Horwood et al., 2006; Kaiser et al., 2011). The management of the NC cod has been split in two units, one north and one south of 62°N, even though the NC cod is not one or two big populations, but consist of several subpopulations (Dahle et al., 2018; Knutsen et al., 2017; Olsen et al., 2010; Wennevik et al., 2008). Each population is thus relatively small, and the “help” from adjacent populations is limited in the form of no “refill” of population and gene flow. These rather small, genetically distinctive populations are thought to be extra vulnerable to external stressors like overfishing, climate change and pollution (Myers et al., 1997). This, in addition to the aggregating behaviour of NC cod during the spawning season, have made them prone to overexploitation. Climate change is also suggested to have impacted the NC cod stock, especially in the southern regions of the Norwegian coast. Changes in climate affects recruitment (Engelhard et al., 2014; Johannessen et al., 2012), growth (Gjøsæter & Danielssen, 2011) and distribution (Freitas et al., 2015) of the cod. Pollution and other anthropogenic impacts disturbing the cod have also been mentioned as causes to why the stock struggles.

1.5 History of the Borgundfjord fishery

The Borgundfjord is one of the adjacent fjords to the city of Ålesund at the west coast of Norway. Each year, from late February to end of April, the cod arrives here to spawn. Hence, there is a gathering of spawning cod on the doorstep of the biggest city in Møre og Romsdal county. This happens among daily arrivals of cruise ships, cargo ships and other activities associated with a coastal city like Ålesund. There are long traditions for fishing cod in the Borgundfjord during the spawning season. Most of this traditional fishing are in the areas covered by the MPA, but there has also historically been substantial fishing in the Hessafjord (Myklebust, 1971).

Since medieval times the Borgundfjord fishery has been going on in a commercial manner, with selling and trading of catches. Fish products have in this way shaped both the economy and where people have settled at Sunnmøre for almost 1000 years (Sørheim, 2004). It is not unreasonable to think that the rich deposits of fish were one of the key pillars of the small medieval town of Borgund, which lays approximately four kilometres east of the Ålesund center (Myklebust, 1971; Sørheim, 2004). Borgund and the Borgundfjord fishery is even mentioned in the Saga of Olaf the Saint in Snorre's Heimskringla, regarding events that allegedly took place at the years from 1027 to 1028 (Korsnes, 2015; Sørheim, 2004). It is said that the reason for the fall of Borgund as a market town in the 1500's was due to a long-lasting period of poor cod catches, but this is not certain.

Cod fishing in Borgundfjord at approximately year 1900. Photo: Musea på Sunnmøre/Aalesunds Museum

This fishery has mainly been important for the residents nearby, but there has also historically been coming fishermen from far away to participate. Hans Strøm, who was a resident chaplain in Borgund from 1750-1763, estimated the total of fishermen participating in the fishery in 1756 to be 2754, where 1260 men were from Borgund and 1494 from other places (Myklebust, 1971). That year, almost 500 boats are said to have been participating in the fishery. Stories about years where the density of boats was so high you could cross the fjord without getting wet on your feet still lives on (Godø, 1977; Korsnes, 2015). This shows the importance and extent of the fishery for the locals living around the Borgundfjord.

A Borgundfjord cod from 1941. Photo: Trygve Aannø

In the later years, the locals are not as dependent on the fishery as earlier years. It is anyhow an important income for some local fishermen, who is not too happy with the ban of commercial fisheries during the spawning season. The fishery also attracts tourists and gives income to the tourism sector. In addition, the fishery remains as an important tradition to many, and the recreational fishing during the spawning season is very popular. In the 1990's the Borgundfjord cod even had its own festival. There is apparently a big willingness to protect the cod in the Borgundfjord, shown by for example the introduction of the MPA. Also, Ålesund municipality started in 2019 a project to clean up pollutants from the fjord bottom. One of the reasons mentioned for doing this, was to maintain the Borgundfjord cod as a "concept and a brand" (Skjong, 2019). The Borgundfjord cod is not only a random fish swimming in the ocean that people see when they scout out of the living room window a cold day in March. It is a part of the local people's DNA.

Cod fishing in the Borgundfjord in March 2020. As seen in the picture, the traditional cod fishery is still popular. Photo: Anne Kristine Tennebø

1.6 Marine Protected Areas (MPAs) and what the Borgundfjord MPA implies

1.6.1 What is a Marine Protected Area, and does it work?

Marine Protected Areas (MPAs) are marine environments protected by limiting human activity. The area can consist of ocean and coastal habitat, with the purpose of achieving conservation goals. It often has a focus either on protecting ecosystems, conserve biodiversity, preserving cultural resources, sustaining or increasing fisheries production or, in some cases, protecting a specific marine species (Claudet et al., 2008; Halpern & Agardy, 2014; NOAA, 2018).

There are different levels of protection within different types of MPAs. Types of MPAs can, roughly, be split in two: extractive and non-extractive (Spalding et al., 2016). Non-extractive MPAs (also called no-take reserves) allow neither extraction nor destruction of living or non-living resources, and often limits and controls the human's impact. The majority of the MPAs are anyhow in the extractive category. These MPAs allow different levels of human activity and extraction, but they should have limited impact on species or the ecosystem (Spalding et al., 2016). Tourism and recreational purposes could be examples of allowed activities as long as the effort is monitored.

Non-extractive marine reserves increase species richness, density, biomass, and organism size (Fenberg et al., 2012; Halpern, 2003; Halpern & Agardy, 2014; Lester et al., 2009). Inside effective MPAs, the large fish biomass can increase five-fold, the number of large species per transect can double, and the shark biomass can increase by fourteen times, when comparing it to fished areas (Edgar et al., 2014). These reserves are useful to achieve conservation benefits no matter the size and age (Fenberg et al., 2012), but increasing the size of the no-take zone and the MPA age can have a positive effect on the density of fish species and species richness within the reserve (Claudet et al., 2008). The effect may however vary from species to species within a reserve, and the effect on a species may vary from reserve to reserve (Lester et al., 2009).

The effects of extractive MPAs, on the other hand, are not as clear. Studies suggest that areas closed for commercial fishing are an ineffective conservation tool, as the fishing pressure from recreational fishing could be just as high in the protected area as outside (Denny & Babcock, 2004). However, areas allowing only recreational fishing with angling, has also shown to increase the annual survival for cod by a substantial amount, as the annual proportion of deaths due to fishing went from 0.59 before to 0.32 after the MPA implementation (Fernández-Chacón et al., 2015). Increased abundance and larger fish has also shown to be the outcome of extractive MPAs, as a result of decreased fishing pressure (Alós & Arlinghaus, 2013).

MPAs that are less effective and that do not have the wanted effect, are caused by two main, broad reasons: inadequacy of design and failure of implementation (Spalding et al., 2016). When it comes to inadequacy of design, boundaries and/or regulations may not be good enough to achieve the objectives of the MPA. What makes a good design is not necessarily easy to point out, but they are often very specific to the ecosystem and location. Failure of implementation often happens when the sites either have small resources or are managed in a bad way, making them contribute little or nothing to conservation (Spalding et al., 2016).

1.6.2 Borgundfjord Marine Protected Area

One of the measures done to reduce the fishing pressure on NC cod, was to implement Borgundfjord as a Marine Protected Area (MPA). The Borgundfjord MPA consists of three spawning areas: Aspevåg, Åsefjord and central Borgundfjord (Figure 1.1). These areas are closed for commercial harvesting, and for private people fishing with nets, during the spawning period from 1st of March till 31st of May. Thus, it is not allowed to fish for neither cod nor other species. There is anyhow one exception: recreational angling is permitted (Johansen et al., 2017). Hence, the Borgundfjord MPA is an extractive MPA, with the goal of protecting the NC cod. There are no restrictions for fishing vessels less than 15 metres (for Danish seine vessels less than 11 metres) outside of the spawning period.

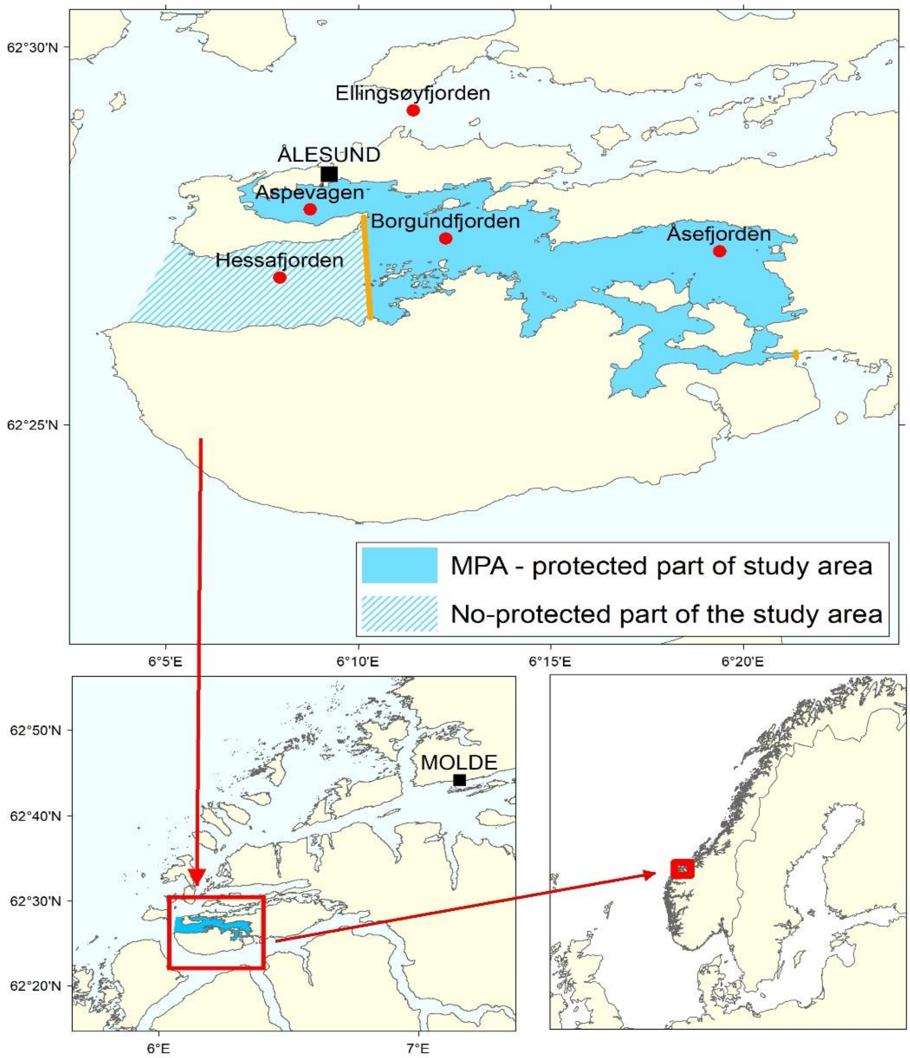

Figure 1.1: The Marine protected area, inside the orange line, consisting of Borgundfjord, Aspevåg and Åsefjord. From 1 March to 31 May this area is closed for fisheries, with only recreational angling being allowed. Hessafjord (hatched lines) is not a part of the MPA, but still a part of the study area.

These restrictions do not apply for Hessafjord (Figure 1.1), but in this area it is, however, not allowed to fish with nets on stakes if the total height of the net and stakes is 23 metres or more (Directorate of Fisheries, 2020). Even though this area is not a part of the MPA, it is included in the estimations of the spawning stock biomass. This is because a substantial amount of spawning takes place in this area, and it is the route of both cod stocks further into the MPA spawning areas. The catch sampling from the Hessafjord has also been used as a part of the spawning stock biomass estimations. Sampling has also been conducted every second time in the Ellingsøyfjord (Figure 1.1), a neighbour fjord to the Borgundfjord, and has been used as a reference to compare the spawning development in the two fjords.

1.7 Objectives

By the implementation of the MPA, it is important to measure its effectiveness, and to make changes if the MPA does not have the wanted effect. Therefore, the ban has been followed up by sampling of cod eggs to estimate the spawning stock biomass. Based on these data, there are 4 main objectives for this thesis:

- Estimate total amount of cod eggs spawned in the fjord, as well as the spawning stock biomass (SSB) for the time series available (2012-2019, no sampling in 2014).
- Describe a standardized way of how to measure SSB in a coastal cod MPA.
- Investigate whether the data collected allows for judgements on whether the introduction of the MPA protects the NCC in a satisfactory manner, and leads to an increase in NC cod spawning in the area.
- Explore potential drivers of fluctuations for the amount of eggs and the estimated SSB in the Borgundfjord MPA.

2 Materials and methods

2.1 Study area

There were four areas of interest: Hessafjord, Borgundfjord, Aspevåg and Åsefjord (Figure 1.1). The three latter ones are part of the MPA, while Hessafjord is the entrance to the MPA. The Ellingsøyfjord (Figure 1.1), a neighbour fjord to the Borgundfjord, was sampled every second time from 2013 onwards and used as a reference to compare the spawning development in the two fjords. All these areas lie around Ålesund, a city on the west coast of Norway, just north of 62°N (Figure 1.1). The MPA area has in total five openings, but the four others than Hessafjord are narrow straits and leads little water compared to Hessafjord (Godø, 1977). Borgundfjord, Åsefjord and Hessafjord has depths exceeding 100 m, while Aspevåg is a bit shallower, with depths barely exceeding 40 m.

2.2 Data collection

The sampling was conducted annually during the spawning season from late February to late April or early May by the Institute of Marine Research (IMR). This was done in cooperation with Runde Miljøsenter between years 2012 till 2019, with an exception in 2014 when no data were collected. There were four fixed stations sampled at every sampling week, and each spawning season consisted of eight sampling weeks. A vertical net haul and measurements of salinity and temperature were performed at each station. The stations were localized in Hessafjord, Aspevåg, Borgundfjord and Åsefjord (Figure 1.1), with one station in each. Usually, the sampling was conducted with two weeks apart in the beginning and the end of the season, and one week apart in the middle of the season. Also, at every second week of egg sampling, a control sampling was conducted with one station in Ellingsøyfjord (Figure 1.1). Notice that Borgundfjord proper is only one of four areas in the survey. The areas in the MPA and in the fishery do however often go under the collective name Borgundfjord, as do the entire fjord system.

2.2.1 Egg sampling

The egg data was sampled by performing vertical hauls with a standard WP2 hand net, which had an inner diameter of 54 centimetres (outer diameter of 60 cm) and a mesh size of 500 µm. The net was hauled at a speed of 0.5 m/s, and was performed from 50 metres depth and up to surface (Espeland et al., 2013). An exception was the station in Aspevåg, where the net haul was taken from 40 metres and up, as there was a risk of hitting the bottom if a 50 metres haul was conducted.

The net was flushed with saltwater to gather the content in the cod-end once it had reached the surface. This content was then transferred to a sample glass, which was marked with station number and date. This was done for each station, before the eggs were brought back to Runde Miljøsenter. There the eggs and larvae were manually sorted into cod and other species. The cod eggs were then sorted by developing stage, ranging from stage 1 to stage 5, according to Thompson & Riley (1981). If there was a high amount of eggs in the sample, it got split in two or four parts to lessen the amount of sorting, counting and separation of egg stages. This was done using a plankton splitter (Figure 2.1).

Figure 2.1: The plankton splitter that has been used for splitting samples. The cylinder part has an outer diameter of 9 centimetres and a height of 15 centimetres, giving it a total volume of 0.95 litres. All sides of the rectangle are 12 cm.

2.2.1.1 Egg species identification – separating cod eggs from other eggs

First, eggs were manually separated from other types of zooplankton using a counting chamber, before the eggs were separated into species. The species of a fish egg can be decided based on factors like the diameter, presence or absence of oil droplets, colour, shape of egg yolk and outer structures. Hence, eggs from cod fish was decided based on the diameter of the egg and further visual inspection, in accordance with Russell (1976). Eggs from a cod fish has a diameter of 1.2 to 1.5 millimetres (Espeland et al., 2013), though some may be larger or smaller, but the majority is in this size range. In addition, cod eggs have no oil droplets. Genetic methods were applied to further separate into NC cod and NEA cod.

Left: Arne Sævik with the net used for hauling. Photo: Kjell Nedreaas
Right: Roger Kvalsund emptying the codend into a sample glass. Photo: William Aannø

2.2.1.2 Separating the cod eggs into stages

All the eggs were separated into development stage ranging from stage 1 to stage 5. This was mainly done as described in Thompson & Riley (1981) (Figure 2.2 and Appendix II, Figure 6.1). The eggs were then stored in glasses with 100 % ethanol, one glass for each stage. Cod larvae were also gathered and stored in an own glass with 100 % ethanol. The eggs and larvae were then sent to IMR for genetic analyses. There, the eggs were genetically tested, to separate them into NC cod and NEA cod, and other species (e.g., haddock) if present. How to genetically separate NC cod from NEA cod is explained in chapter 2.4.4.

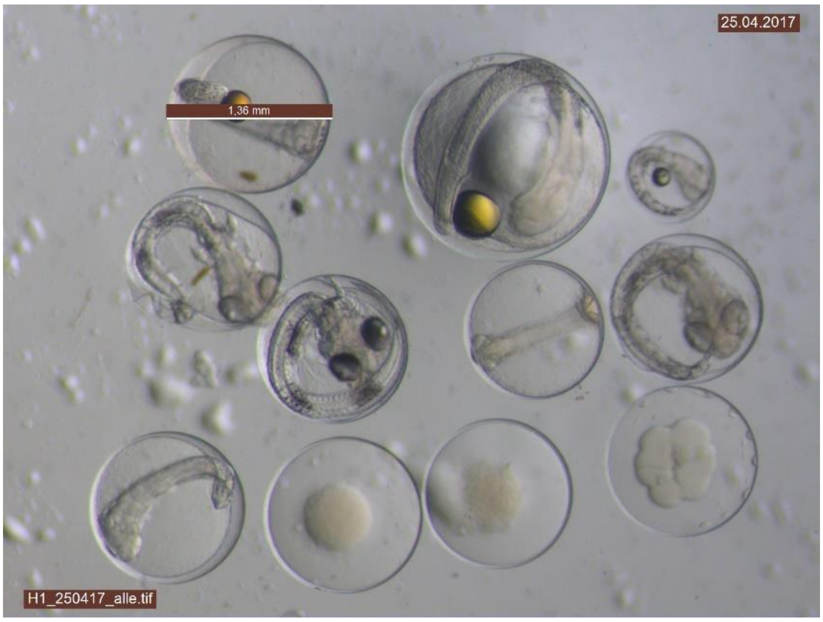

Figure 2.2: Overview of different stages and species that could be found in a sample. Eggs in the top row (from left to right) are in stage 3, 4 and 4, respectively. Eggs in second row are in stage 4, 5, 2 and 4, while the eggs in bottom row are in stage 3, 1, 1 and 1. All eggs are cod eggs, except from eggs in the top row, which likely are Brosme brosme, Argentina sphyraena and a species from the Phycidae family. The presence of oil droplets in the eggs in the top row tells us that it is not cod eggs. Photo: Roger Kvalsund at Runde Miljøsenter

2.2.2 Hydrographic measurements

In addition to the net hauls, both temperature and salinity were measured at depths with varying intervals from the bottom to the surface (Appendix III and IV). These hydrographic measurements were conducted using a SAIV (SD 204) CTD probe.

The SD204 model from SAIV A/S. Photo: www.saiv.no

2.2.2.1 Testing for statistically significant differences in temperature from year to year

A one-way ANOVA was performed to check for significant temperature differences ($p < 0.05$) between the years (Eq. 2.1). The first line of equation 2.1 creates a one-way ANOVA model, while the second line gives the output of the ANOVA function. A post-hoc multiple comparisons test (Tukey HSD) was then performed to compare and see what years that differed from each other (Eq. 2.2), using *library(multcomp)* in R. The first line of equation 2.2 creates the multiple comparisons test, while the second line shows the result of the test. These data analyses were conducted in RStudio version 3.5.3 (R Core Team, 2019).

```
fit.lm ← lm(Temperature~Year, data=temperature)
anova(fit.lm)                                                        (2.1)
```

```
mc ← glht(fit.lm, linfct=mcp(Year="Tukey"), data=temperature)
summary (mc)                                                         (2.2)
```

The temperature values that were compared for each season was the mean temperature from 2 to 40 m of each station in the five weeks with the most eggs.

2.2.3 Cod landings

Each season, Møreforsking AS sampled spawning cod from the commercial gillnet fishery in the Hessafjord (as this was the only placed allowed to fish). Age, length, weight, maturity stage and sex were determined from each cod caught. The mesh sizes of the commercial gillnet varied from 186 to 239 mm, where a mesh size of 193 mm was most frequently used.

2.2.3.1 Age determination, weight, length and sex

Each cod from the landings from Hessafjord was measured, both in weight and length. Their age, sex and type of cod were determined. Age was found by counting the number of annual rings or growth zones in the otoliths, while sex was found looking at the gonads. Type of cod was also found using the otolith growth zone structure, which has been the traditional way of separating them (Rollefsen, 1933). This can be done for cod older than two years, i.e., by checking the shape and relative distance between the two innermost transparent zones of the otolith (Berg & Albert, 2003; Johansen et al., 2017; Rollefsen, 1933). The two innermost transparent zones can be used, because NC cod grows faster in the first years and thus the shape and the distance between the first zones are different and bigger compared to NEA cod.

Hence, from cod landings in Hessafjord, the average weight, average length and proportion of females were estimated and used in the SSB estimations.

2.2.3.2 Condition factor

Fulton’s condition factor (K) was used to calculate the condition of female NC cod (Eq. 2.3).

$$K = 100 * \frac{W}{L^3} \tag{2.3}$$

Where W is the weight of the fish, and L is the length of the fish. When using Fulton's condition factor, it is assuming a fish with isometric growth (β=3), but cod does not necessarily follow this type of growth. Fulton's condition factor can however still determine a general condition of the cod. Thus, years with particularly good or bad condition of the cod will be observed in the condition estimates.

Significant differences were also estimated for the female cod condition. This was done using Equation 2.1 and 2.2, where the data for temperature were replaced with data for female cod condition.

2.2.3.3 Estimating mortality

The key aspect behind the MPA implementation, was to lower the mortality of the NC cod stock. To check if this had happened, both the instantaneous (Z) and annual (A) mortality rate were estimated for 1996, 2002, 2009, and 2012-2019 (excl. 2014). This was done using a catch-curve regression method, based on the instructions found in Ogle (2013). It was decided to use the catch of a single year to estimate the mortality, which is called cross-sectional data as it "crosses" several cohorts of the fish. As younger fish does not have the same vulnerability to the fishery gear, only the ages from the peak age to the oldest age of the sample was used, which often was from 6-7 years to 11-12 years. The mortality rates, in this case with NC cod caught in 2012 as an example, was found using equation 2.4. These data analyses were conducted in RStudio version 3.5.3 (R Core Team, 2019), using *library(FSA)*.

```
cm ← data.frame(age=3:11, ct=c(2,10,38,51,58,16,13,3,2))
cm$logct ← log(cm$ct)
ncc ← catchCurve(ct~age, data=cm, ages2use=7:11)
summary(ncc)
confint(ncc)
```
(2.4)

The first line contains the ages found in the sample and the respective amount of cod of that age, the ages used in line three goes from the peak age to the oldest in the sample, and the two last lines give the output of mortality rate and its 95 % confidence interval.

There are several assumptions being made when using this method: (i) closed population, meaning no immigration or emigration; (ii) constant mortality, meaning that the mortality is independent of year and age; (iii) constant vulnerability, meaning that the fish has the same vulnerability to the fishery independent of age and year; (iv) unbiased sample regarding agegroups; (v) constant recruitment, meaning that the initial number of individuals is the same for each cohort (Ogle, 2013).

2.3 Modelled particle drift as a proxy for egg drift

The amount of eggs in the fjord could be affected by currents in the area. It was therefore decided to see if the currents could have caused differences in amount of eggs in the samples between the years. As it is a close to impossible task to observe where the eggs drifts, mathematical current models have to be used to estimate where they are likely to drift. A high-resolution hydrodynamical model based on the methods and results described in Asplin et al. (2020) has been run by the Institute of Marine Research. The model has a 160m x 160m horizontal resolution, covers the coastal area between Stadt and Hustadvika and is run for the period 2013-2019. Hence, existing files with hourly values for the current were used to make a simulation of where the eggs would have drifted 4 and 30 days after given dates. Four-day drift was chosen because the stage 1 eggs were maximum four days old, and 30 days was chosen to see the general long-term drift of the pelagic phase.

Each sampling day was modelled, where the amount of stage 1 and 2 eggs found in the sampling was scaled up five times to get a more statistically trustworthy result. The eggs were then released at the four different stations according to the quantity sampled. The depth of each individual egg particle was constant throughout the modelled time, but the depths of each batch of egg-particles were defined based on a Gaussian distribution, with 15 m and 10 m as the mean and standard deviation, respectively. To ensure a realistic representation of depths, all eggs were released between 2 and 50 m depth in the particle drift model. The location of each egg after 4 and 30 days was then recorded and stored. From this, an estimation of the proportion of eggs that had drifted out of the area was retrieved. A more detailed description of a similar modelling effort and analysis is described in Espeland et al. (2015).

2.4 Estimating total amount of NC cod and NEA cod eggs spawned in a season

For these calculations, only stage 1 eggs were included. This was to get the window of when the eggs were spawned to be as narrow as possible, to lessen the impact of factors like mortality and drift had on the amount of eggs collected.

2.4.1 Overview of the estimation procedure

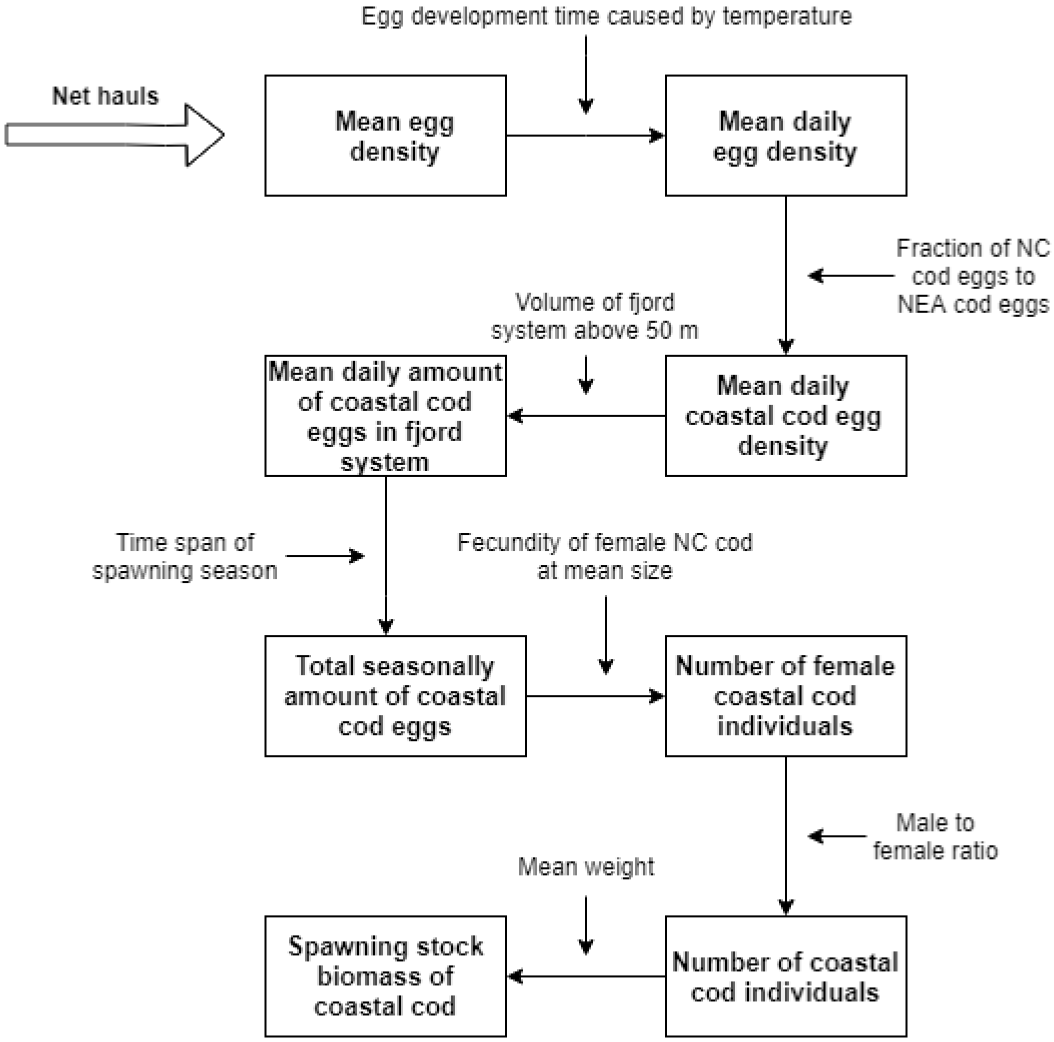

Figure 2.3: Overview of the estimation procedure for the spawning stock biomass of NC cod within each year, with the inputs (outside of boxes) and the outputs (inside of boxes). The same procedure was done for NEA cod, where the values for NC cod were replaced with values for NEA cod.

2.4.2 Interpolation

In cases where there were two weeks between samplings (often in the beginning and the end of the season), it was decided to do an interpolation for the week in between. That will say, the unknown number of eggs in a week between two sampling weeks was decided by using mean value of the week before and the week after (Eq. 2.5). This was done to get values for each week during the spawning season, which again was important to get a more accurate mean for the whole season. Without the interpolations, the seasonal average daily egg density (Eq. 2.9.3) was likely to be higher than it should, as the weeks in the middle of the season would be more emphasized.

$$Eggs\ in\ an\ unsampled\ week = \frac{Eggs\ week\ before + eggs\ week\ after}{2} \qquad (2.5)$$

Doing the interpolations was likely to improve the results, as we did not get longer periods with no data values. The spawning seasons had a dome shaped curve, and it was therefore assumed that the interpolation values were reasonable.

2.4.3 Temperature's effect on development of the cod egg stages

The development of the cod's eggs is separated into five stages, before it reaches the larvae stage (Thompson & Riley, 1981). How long the eggs stay in each stage depends on the temperature. Colder temperatures slow the development, while warmer temperatures increase it. Hence, a colder temperature increases the time span the eggs are in each stage, and vice versa with warmer temperatures. As only stage 1 eggs were used in the calculations, the first step was to estimate the time it would take for the eggs to develop from stage 1 to stage 2, and in this way estimate a time window of when the stage 1 eggs caught were spawned. This was done using equation 2.6, which was based on an equation derived from Thompson & Riley (1981).

$$D = 10^{(A*T)+B} \quad (2.6)$$

Where D is the amount of days from fertilization to the end of each stage, T is the average temperature from 2-40 metres depth, and A and B are regression coefficients. The values of A and B were gathered from a table derived from Thompson & Riley (1981) (Appendix VI), while T was derived from the hydrographic measurements. D was calculated for each station in each week.

2.4.4 NC cod to NEA cod relationship: Genetically separating between NC cod and NEA cod eggs

Since both NC cod and NEA cod spawn in the fjord during the same time period, and NC cod is the species of interest, it was necessary to determine how much of the eggs collected that were spawned by NC cod and how much were spawned by NEA cod. This was found using genetic analyses, which was done for each station on each sampling day. Usually, only the results from stage 1 eggs were used, but other stages could be included if the sample was too small to get trustworthy results.

Separating the two stocks genetically was based on the Pan I (or Pantophysin) locus. The allele frequency of this locus vary in great extent between NEA cod and NC cod, and using this allele frequency has shown to be an effective way to separate them (Fevolden & Pogson, 1997; Michalsen et al., 2014; Sarvas & Fevolden, 2005a; Wennevik et al., 2008). The *Pan* I locus has two alleles, called *Pan* I^A and *Pan* I^B. NEA cod has a large fraction of the *Pan* I^B

allele (p~0.90), while NC cod has a large fraction of the *Pan* I^A allele (p~0.80) (Fevolden & Pogson, 1997; Johansen et al., 2017; Sarvas & Fevolden, 2005b; Wennevik et al., 2008). This difference in allele frequencies applies to the two stocks regardless of age (Sarvas & Fevolden, 2005a). The fraction of the two alleles may however vary within both NEA cod and NC cod, and you might find NC cod stocks with lower fraction of the Pan I^A allele and vice versa with NEA cod (Sarvas & Fevolden, 2005b).

Hence, the estimation of NC cod to NEA cod relationship was based on the genotypes at the Pan I locus. Both NC cod and NEA cod could have the genotypes AA, BB and AB, even though NEA cod rarely has the AA type and NC cod rarely has the BB type (Michalsen et al., 2014; Wennevik et al., 2008). Because of this, it was not possible to find the fraction by assigning one and one egg as either NC cod or NEA cod. Instead, the fraction of NEA cod in each sample was estimated by equation 2.7.

$$Fraction_{NEAC} = \frac{FractionB - \alpha}{1 - 2\alpha} \qquad (2.7)$$

Where $FractionB$ is the observed fraction of the Pan I^B alleles (number of Pan I^B alleles divided by combined number of Pan I^B and PanI^A alleles) in the sample, and α is the expected fraction of Pan I^B alleles if the sample had consisted of only NC cod. There have been studies indicating a value of α as both 0.10 (Wennevik et al., 2008) and 0.05 (Sarvas & Fevolden, 2005b). $Fraction_{NEAC}$ was therefore estimated for both values of α, where the average of these two estimates was used.

2.4.5 Calculating daily egg density for NC cod and NEA cod

The daily egg density of NC cod (eggs/m^3/day) were calculated for each haul, using equation 2.8.1.

$$x_{NCC} = \left(\frac{\frac{N_{sample}}{V_{sample}}}{\frac{D}{2}} \right) * (1 - Fraction_{NEAC}) \qquad (2.8.1)$$

Where x_{NCC} was daily egg density of NC cod (eggs/m^3/day), N_{sample} was the number of eggs in the sample, V_{sample} was the volume of water filtrated (m^3) in the net haul, D was the development time (Eq. 2.6), and $Fraction_{NEAC}$ was the fraction of NEA cod found in the genetic analysis (Eq. 2.7).

Equation 2.8.2 was used get the daily NEA cod egg density (egg/m^3/day):

$$x_{NEAC} = \left(\frac{\frac{N_{sample}}{V_{sample}}}{\frac{D}{2}} \right) * Fraction_{NEAC} \qquad (2.8.2)$$

The estimations of daily egg density for NC cod and NEA cod were done for each sampling event.

V_{sample}: The WP2 net had an inner diameter of 0.54 metres, which gave a radius of 0.27 metres. Based on this, the area of the net opening was found to be 0.2289 m^2. Hence, the stations in Hessafjord, Borgundfjord and Åsefjord had ~11.4 m^3 of water filtrated each (as the net haul started at 50 metres), whereas the station in Aspevåg had ~9.2 m^3 water filtrated (net haul started at 40 metres).

$\frac{D}{2}$: D represents the amount of days for the eggs to develop from stage 1 to stage 2, given a certain temperature. This was typically found to be between 3 and 4 days. Hence, the eggs caught could have been spawned the last 3 to 4 days. This number was then divided by 2, to compensate for egg losses (due to mortality and drift of eggs out of the area) and in that way get closer to an average age of the stage 1 eggs collected in the net.

2.4.6 Standard error of average daily egg density

There was one value of x_{NCC} for each station for each week. The week average for NC cod was then found using equation 2.9.1.

$$\bar{x}_{j_{NCC}} = \frac{\sum_{i=1}^{k} x_{j,i_{NCC}}}{k} \qquad (2.9.1)$$

Where $\bar{x}_{j_{NCC}}$ is the average daily egg density of NC cod for week *j*, *k* is the number of stations sampled in week *j*, and $x_{j,i_{NCC}}$ is the number of eggs at station *i* in week *j*. Equation 2.9.2 was then used to find the variance of $\bar{x}_{j_{NCC}}$.

$$var(\bar{x}_{j_{NCC}}) = \frac{var(x_{j,i_{NCC}})}{k} = \frac{\sum_{i=1}^{k} \left(x_{j,i_{NCC}} - \bar{x}_{j_{NCC}} \right)^2}{(k-1)*k} \qquad (2.9.2)$$

Then the seasonal average of daily NC cod egg density was found using equation 2.9.3.

$$\bar{X}_{NCC_{avg}} = \frac{\sum_{j=1}^{n} \bar{x}_{j_{NCC}}}{n} \qquad (2.9.3)$$

Where *n* is the number of weeks estimated or sampled. Equation 2.9.4 was then used to find the variance of $\bar{X}_{NCC_{avg}}$.

$$var\left(\bar{X}_{NCC_{avg}}\right) = var\left(\frac{\sum_{j=1}^{n}\left(\bar{x}_{j_{NCC}}\right)}{n}\right) = \frac{\sum_{j=1}^{n} var\left(\bar{x}_{j_{NCC}}\right)}{n^2} \qquad (2.9.4)$$

This was again used to find the standard error of the seasonal average of daily egg density (Eq. 2.9.5):

$$s.e. = \sqrt{var\left(\bar{X}_{NCC_{avg}}\right)} \qquad (2.9.5)$$

Equation 2.9.1 – 2.9.5 was also calculated for NEA cod, where the values for NC cod were replaced with values for NEA cod.

2.4.7 Total number of eggs

Using the $\bar{X}_{NCC_{avg}}$ (Eq. 2.9.3), the total number of NC cod eggs in the whole season was found using equation 2.10.1.

$$T_{NCC_{eggs}} = \bar{X}_{NCC_{avg}} * D_{season} * U_{total} \qquad (2.10.1)$$

where $T_{NCC_{eggs}}$ is the total amount of NC cod eggs, D_{season} is number of days in the season and U_{total} is the total number of m^3 (above 50 m depth) in the whole sampling area. The 95 % confidence interval was then found using equation 2.10.2.

$$95\ \%\ C.I. = (\bar{X}_{NCC_{avg}} \mp 2s.e.) * D_{season} * U_{total} \qquad (2.10.2)$$

These calculations (Eq. 2.10.1 and Eq. 2.10.2) were also done for NEA cod, where the values for NC cod were replaced with values for NEA cod.

2.5 Estimating spawning stock biomass (SSB)

2.5.1 Fecundity estimates

The fecundity of NC cod in Borgundfjord was estimated using equation 2.11.1. This equation was derived from a plot made by Hannes Höffle (IMR), where length was plotted against potential fecundity for NC cod caught within and around Borgundfjord (Hannes Höffle, IMR, pers. comm.) (Appendix VIIIa).

$$Fec_{NCC} = (2 * 10^{-6} * \bar{L}^{3.2786}) * 10^{6} \qquad (2.11.1)$$

Where Fec_{NCC} is the fecundity of NC cod females and $\bar{L}$ is the mean length of female NC cod caught in Hessafjord during each spawning season.

The fecundity of NEA cod was found using equation 2.11.2. This equation was derived from a plot where length was plotted against potential fecundity for NEA cod caught in Lofoten and the Barents Sea (Hannes Höffle, IMR, pers. comm.) (Appendix VIIIb).

$$Fec_{NEAC} = \left(0.0533 * E^{(0.0465*\bar{L})}\right) * 10^6 \qquad (2.11.2)$$

Where $Fec_{NEAC}$is the NEA cod fecundity and $\bar{L}$ is the mean length of female NEA cod caught in Hessafjord during the spawning season that was estimated.

2.5.2 Spawning stock biomass (SSB)

When the total amount of eggs was found, the values of fecundity, average weight and female proportion were used to estimate the SSB, as shown in equation 2.12.

$$SSB = \frac{\frac{T_{NCC_{eggs}}}{Fec_{NCC}}}{R_{NCC}} * \bar{w}_{NCC} \qquad (2.12)$$

Where R_{NCC} is the fraction of NC cod females to males, and $\bar{w}_{NCC}$ is the overall average weight of NC cod. These values were retrieved from the commercial catches in Hessafjord. The 95 % confidence interval was found by replacing $T_{NCC_{eggs}}$with the upper and lower egg values found in equation 2.10.2.

This SSB estimation was done the same way for NEA cod, but the values for NC cod were replaced with the values for NEA cod.

2.5.3 Estimating uncertainties for weight and length

There are also uncertainties for the average weight used in the SSB estimate and for the average female length used in fecundity estimates. There was not found a way to implement these uncertainties in the final SSB estimates. Therefore, the 95 % confidence interval for these values were calculated individually to see how much of an impact they could have had on the final estimates.

First, the standard deviation for length was found using equation 2.13.1, where N is the number of cod in the sample, l_i is the length of cod i, and $\bar{l}$ is the mean length of the whole sample.

$$s = \frac{\sum_{i=1}^{N}(l_i - \bar{l})^2}{N-1} \qquad (2.13.1)$$

The 95 % confidence interval for length was found using equation 2.13.2, where *s* is the standard deviation.

$$95\%\ C.I. = \bar{l} \mp 1.96 * \frac{s}{\sqrt{N}} \qquad (2.13.2)$$

To find the 95 % confidence interval for weight, the same formulas were used, but the values for length were replaced with values for weight.

3 Results

3.1 Data collection

3.1.1 Egg sampling

The spawning started late February and ended late April or early May, with a top in spawning activity late March or early April. Hence, the spawning followed a bell-shaped curve, with the highest spawning activity mid-season. 2017 was the year with the lowest amount of stage 1 eggs collected, while 2013 was the year with the highest amount of stage 1 eggs collected (Figure 3.1). The few eggs in the start and the end of the seasons, show that the spawning seasons have been well capsulated by the sampling. Aspevåg had an unusually high amount of eggs over two weeks in 2013, while the other areas that year were more normal.

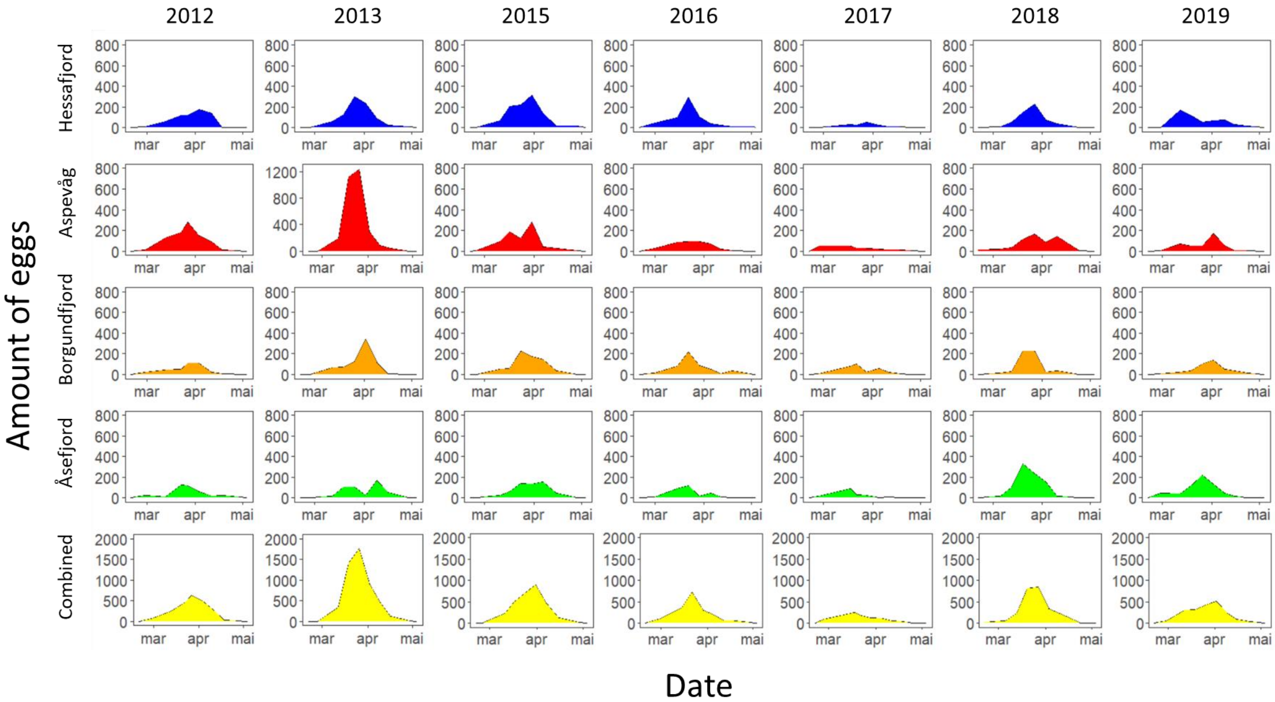

Figure 3.1: Amount of stage 1 eggs collected at the different stations from year to year. Notice that the y-axis for Aspevåg in 2013 goes to 1200 eggs, while the rest goes to 800 eggs. The bottom row (combined) goes to 2000 eggs.

There was a clear positive correlation between the amount of cod eggs in stages 1-2 and cod eggs in stages 3-5 (R^2 = 0.77). Hence, there was a rather even loss of eggs from year to year, assuming that the relationship between total amount of stage 1-2 eggs and total amount of stage 3-5 eggs corresponds to the egg loss. 2019 had the highest loss, with ~77 % of eggs lost from stage 1-2 to stage 3-5. 2012 had the lowest loss, with 57 % of eggs lost (Table 3.1 and Figure 3.2).

Table 3.1: Seasonal amount of eggs stage 1-2 and stage 3-5, with loss of eggs estimated based on these amounts

Year	Stage 1-2	Stage 3-5	Loss of eggs
2012	3253	1398	57.0 %
2013	6098	1805	70.4 %
2015	3585	1448	59.6 %
2016	2370	1029	56.6 %
2017	1251	549	56.1 %
2018	4304	1657	61.5 %
2019	2758	623	77.4 %

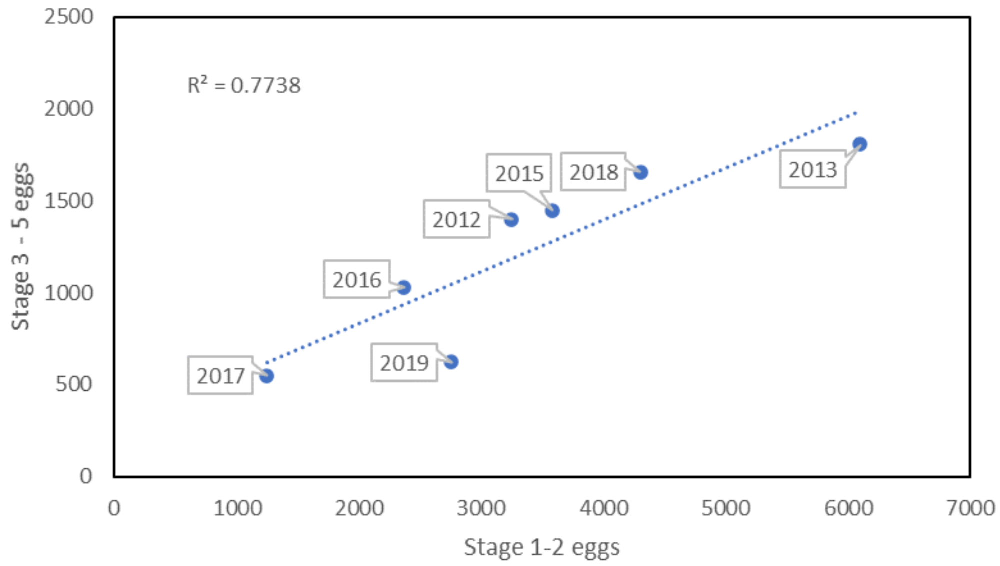

Figure 3.2: There was a clear positive correlation (R^2 = 0.77) between seasonal amounts of stage 1-2 cod eggs and stage 3-5 eggs.

Most of the years had a gradually drop in amount of eggs from stage to stage. However, there were collected more stage 3 eggs than stage 2 eggs in 2013, 2015 and 2016. In addition, in 2013 more larvae than stage 5 eggs were collected (Table 3.1). There did also seem to be some correlation (R^2 = 0.65) between the amount of cod eggs and the amount of eggs from other species that were collected each season (Figure 3.3).

Table 3.2: Total amount of eggs and larvae collected in all areas, excluding Ellingsøyfjord, in the different stages in the different years.

Year	Stage 1	Stage 2	Stage 3	Stage 4	Stage 5	Larvae	Other species' eggs (+ larvae)
2012	2234	1019	989	344	65	38	1324
2013	5012	1086	1404	323	78	103	3318 (+102)
2015	2988	597	1188	180	80	60	2573 (+26)
2016	1802	568	817	170	42	16	1025 (+52)
2017	842	409	371	153	25	23	790 (+37)
2018	2546	1758	1222	325	110	45	1325 (+151)
2019	1965	793	424	120	79	16	1552 (+76)

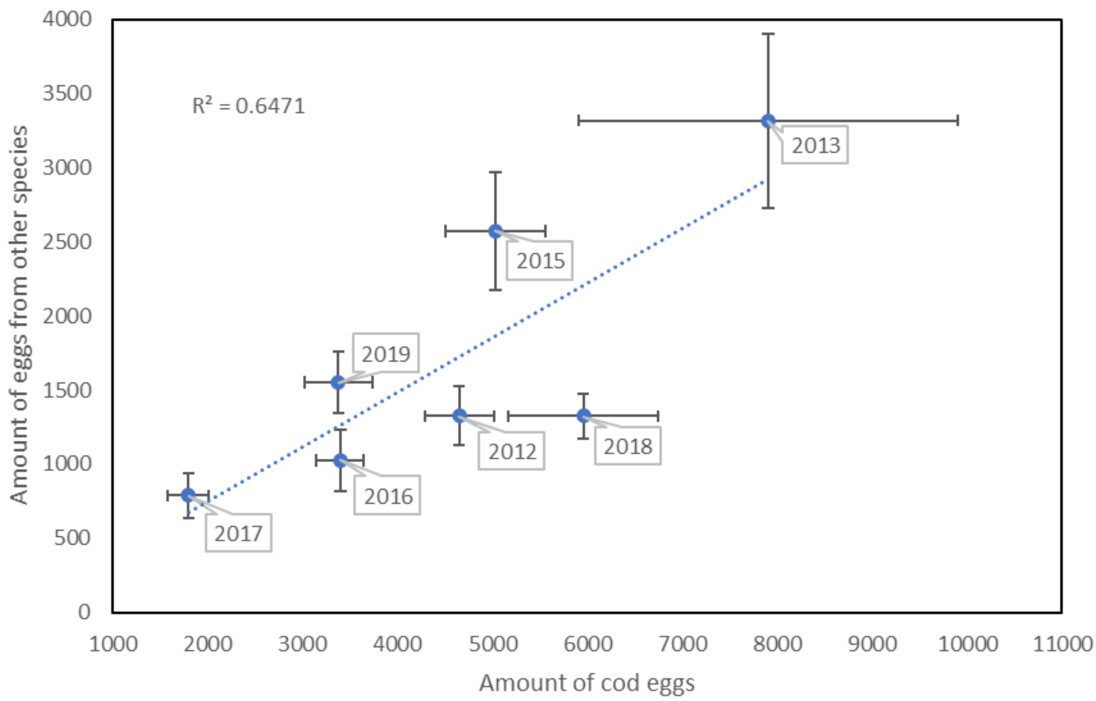

Figure 3.3: Number of cod eggs in stage 1-5 and number of eggs from other species showed some correlation, with a R^2 of 0.65. The error bars show the 95 % confidence interval. Values from Ellingsøyfjord is excluded.

3.1.2 Hydrography

3.1.2.1 Salinity

The salinity fluctuated somewhat from year to year in Hessafjord and Aspevåg, where the mean was highest in 2019 (~33.7 ppt) and lowest in 2015 (~32.6 ppt) (Figure 3.4).

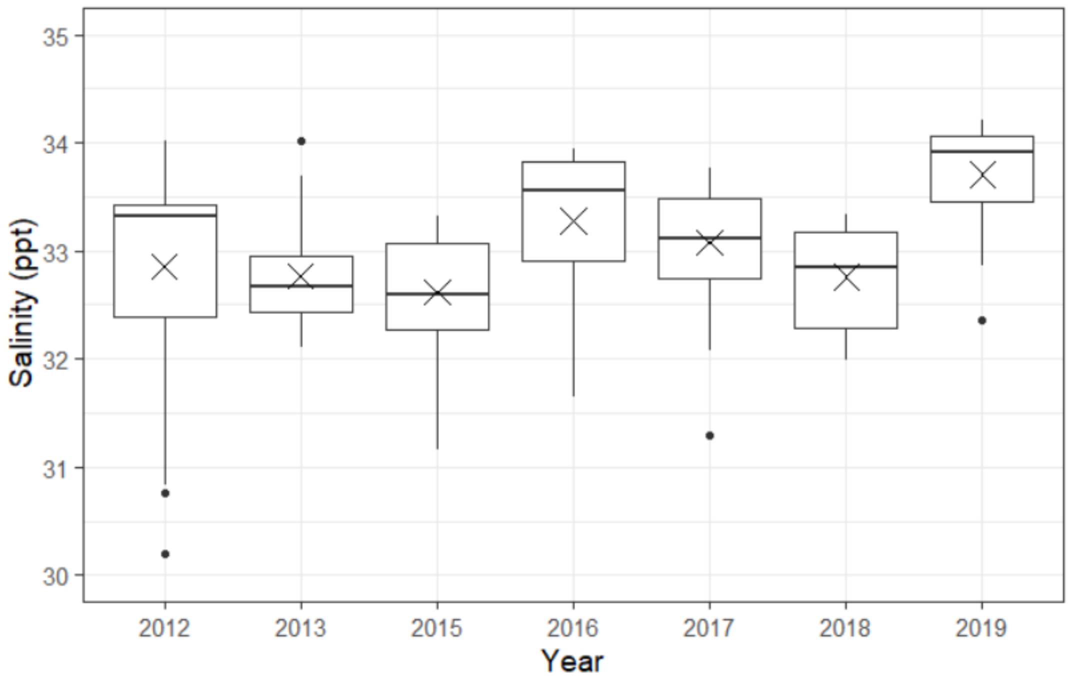

Figure 3.4: Salinity for Hessafjord and Aspevåg for the different years. The values used for each year are the salinity at 2, 10, 20, 30 and 40 metres depth in Hessafjord and Aspevåg for the five weeks with the highest spawning activity. The cross

shows the mean salinity, the horizontal line shows the median (50th percentile), the box shows the 25th to 75th percentile, the vertical lines exiting the boxes show the error bars, while the dots are outliers.

3.1.2.2 Temperature

Usually, the mean temperature at 2-40 m depth during the spawning period was around 6°C. However, 2013 and 2018 stands out as colder years with temperatures ranging just above 4°C (Figure 3.5). The temperature varied significantly ($p<0.05$) between many of the study years, where 2013 and 2018 were significant different from all the other years, but not from each other. 2019 were also significant different from many of the study years (Table 3.3). Since there were significant differences in mean temperatures between the years, we got a more accurate estimate when including different temperatures from year to year, regarding the effect of temperature on egg development (see chapter 2.4.3).

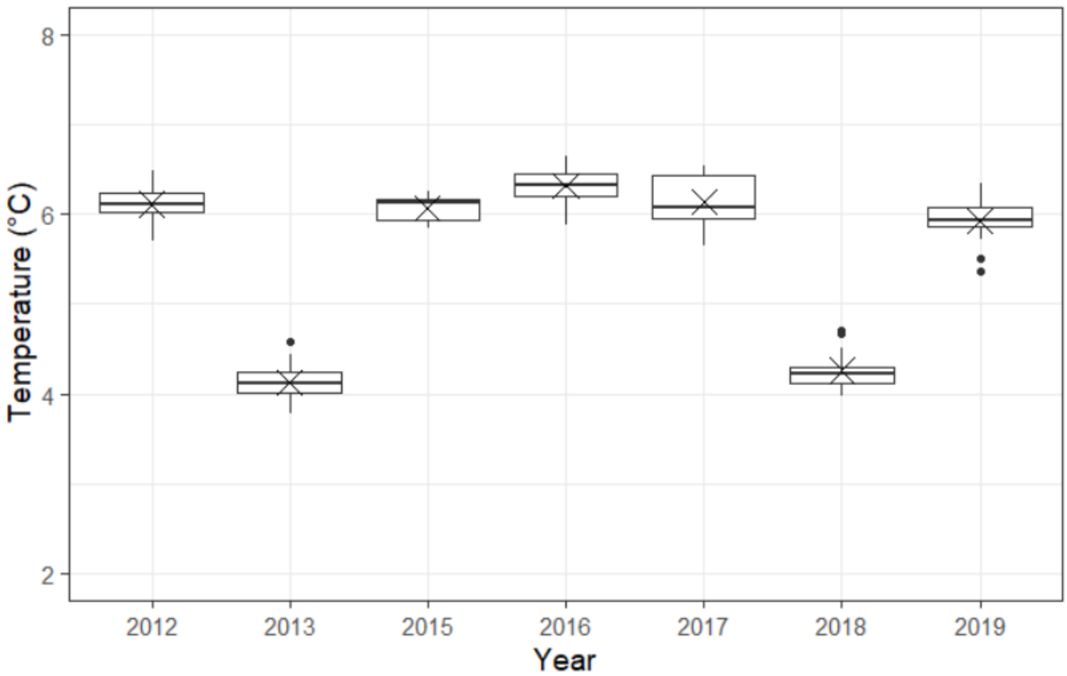

Figure 3.5: Boxplot showing how the temperature in the spawning season varied from year to year. The values used for each season was the mean temperature (from 2 to 40 m) of each station in the five weeks with the most eggs. The cross shows the mean temperature, the horizontal line shows the median (50th percentile), the box shows the 25th to 75th percentile, the vertical lines exiting the boxes shows the error bars, while the dots are outliers.

Table 3.3: The results from ANOVA test showing if the temperature differences from season to season was statistically significant. The values in bold indicates a significant difference (p<0.05).

	2012	2013	2015	2016	2017	2018	2019
2012		**<0.001**	0.994	0.063	0.999	**<0.001**	0.097
2013			**<0.001**	**<0.001**	**<0.001**	0.435	**<0.001**
2015				0.008	0.932	**<0.001**	0.379
2016					0.169	**<0.001**	**<0.001**
2017						**<0.001**	**0.032**
2018							**<0.001**
2019							

3.1.3 Cod landings

3.1.3.1 Age, length, weight and sex

The landings in Hessafjord had a substantially higher amount of NC cod than NEA cod for each year (Table 3.4). Typically, the landings also contained more males than females, with some exceptions. There were caught only 5 NEA cod in 2017, which is not a high enough amount to get representative data values.

Table 3.4: Total number of cod caught in Hessafjord for the age, length, weight and sex data, split in numbers for type of cod (NCC and NEAC) and gender.

Year	Number of gillnet samples	Number of cod	Number of NCC				Number of NEAC				Unknown cod type
			Overall	*Females*	*Males*	*Unknown gender*	*Overall*	*Females*	*Males*	*Unknown gender*	
2012	5	232	193	107	86	0	36	14	22	0	3
2013	3	144	118	50	68	0	25	10	15	0	1
2015	5	194	171	80	91	0	23	15	8	0	0
2016	5	240	203	88	115	0	34	20	14	0	3
2017	2	57	52	20	32	0	5	2	3	0	0
2018	4	174	126	45	64	17	14	3	7	4	34
2019	4	208	169	84	69	16	37	9	23	5	2

Landings of Norwegian coastal cod

There was typically a higher fraction of males than females, with exceptions in 2012 and 2019. The female NC cods were consistently larger than the males, both in weight and length. The average female length varied from 83 cm in 2013 to 90 cm in 2012. The length range was narrow, with the highest standard error of the mean in 2017 of 5 cm. The overall average weight varied from 6.1 kg in 2018 to 7.7 kg in 2012. The weight range was also highest in 2017, with a standard error of 0.8 kg (Table 3.5).

Table 3.5: Data for NC cod gathered from cod caught in Hessafjord. The numbers in bold were used in the SSB estimations, and the numbers in parenthesis is the 95% confidence interval. Fraction female equals R in equation 2.12 and the overal.

Year	Mean length (cm)			Mean weight (kg)			Number of cod	Fraction female
	Overall	Female	Male	Overall	Female	Male		
2012	86	**90** (∓2)	81	**7.7** (∓0.5)	9.0	6.2	193	**0.55**
2013	82	**83** (∓3)	81	**6.9** (∓0.5)	7.6	6.3	118	**0.42**
2015	83	**86** (∓2)	79	**7.2** (∓0.5)	8.5	6.0	171	**0.47**
2016	83	**87** (∓2)	80	**6.8** (∓0.4)	7.8	6.1	203	**0.43**
2017	81	**87** (∓5)	77	**6.4** (∓0.8)	8.2	5.4	52	**0.39**
2018	82	**85** (∓3)	78	**6.1** (∓0.4)	7.0	5.3	126	**0.41**
2019	84	**87** (∓3)	81	**7.2** (∓0.5)	8.1	6.1	169	**0.55**

Landings of Northeast Arctic cod

Same as for NC cod there was typically a higher fraction of males than females of NEA cod, with an exception in 2015 and 2016. The females were also consistently larger than the males, with an exception in 2017. That year only two gillnet catches, containing only 5 NEA cod (Table 3.4), were sampled for length, weight, age and gender, making the values less likely to be representative of the actual composition of weight, length and sex ratio. The average length of female NEA cod varied from 95 cm in 2018 to 101 cm in 2015, while the average overall weight varied from 7.2 kg in 2018 to 10.0 kg in 2015. The ranges of length and weight data were larger for NEA cod than for NC cod (Table 3.6).

Table 3.6: Data for NEA cod gathered from cod caught in Hessafjord. The numbers in bold were used in the SSB estimations, and the numbers in parenthesis is the 95 % confidence interval.

Year	Mean length (cm)			Mean weight (kg)			Number of cod	Fraction female
	Overall	Female	Male	Overall	Female	Male		
2012	88	**96** (∓5)	83	**6.8** (∓1.0)	8.9	5.5	36	**0.39**
2013	92	**96** (∓6)	90	**8.2** (∓1.2)	10.1	6.9	25	**0.40**
2015	98	**101** (∓5)	92	**10.0** (∓1.5)	11.3	7.7	23	**0.65**
2016	95	**97** (∓3)	91	**8.8** (∓0.8)	9.7	7.5	34	**0.59**
2017	97	**97** (∓4)	97	**9.6** (∓1.5)	9.1	9.9	5	**0.40**
2018	91	**95** (∓2)	88	**7.2** (∓1.0)	7.5	7.2	14	**0.30**
2019	93	**97** (∓10)	91	**8.4** (∓1.2)	10.5	7.6	37	**0.28**

Age composition

A large proportion of the NC cod caught was 6 or 7 years old, followed by cod at 5 or 8 years (Figure 3.6). The NC cod in 2019 was slightly older than the other seasons, with a substantial amount of 8 years old cod. The dominating age of NEA cod fluctuated between the years, but they were typically between 8 to 11 years old, i.e., somewhat older than the NC cod. The merged age compositions showed that the age of cod caught in Hessafjord followed a bell-shaped curve, with a top at 6-7 years. The age distribution of NEA cod showed a much more flattened curve, with a top at approximately 9 years (Figure 3.7). Hence, the NEA cod entering the area is older than the coastal cod coming there to spawn. The catch at age estimate from the commercial fisheries in Norwegian coastal areas for 2018 show the same pattern in age distribution for both NC cod and NEA cod (Figure 2.3a in ICES, 2019b) as the data collected in this study (Figure 3.7).

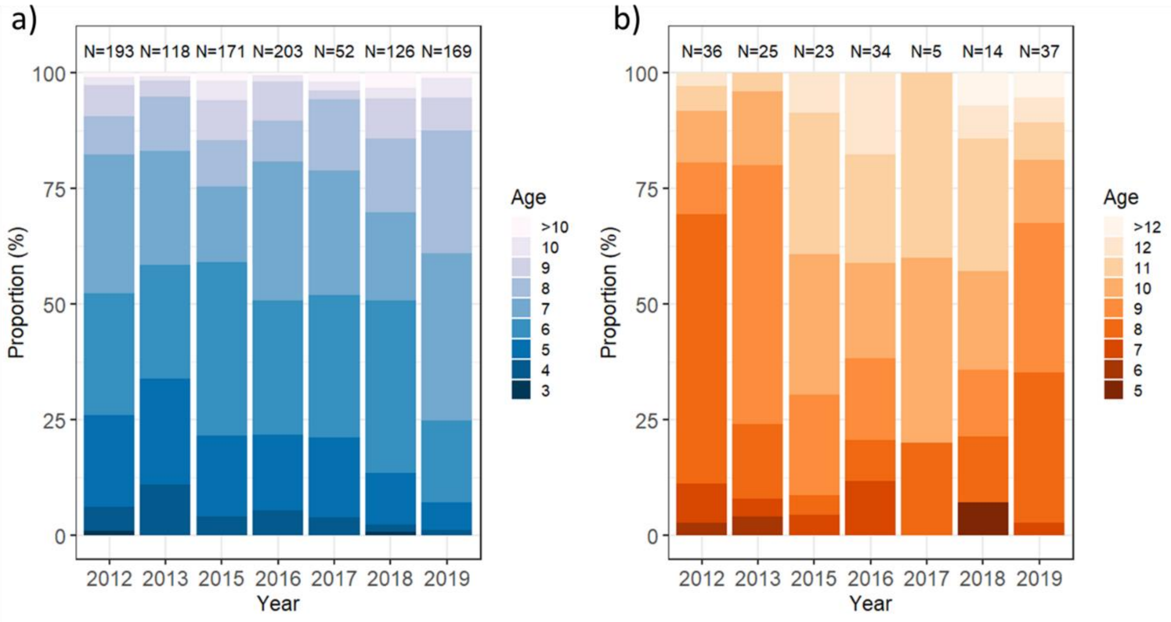

Figure 3.6: Age composition of a) NC cod and b) NEA cod caught in Hessafjord during the spawning season. N is the number of age determined cod each year.

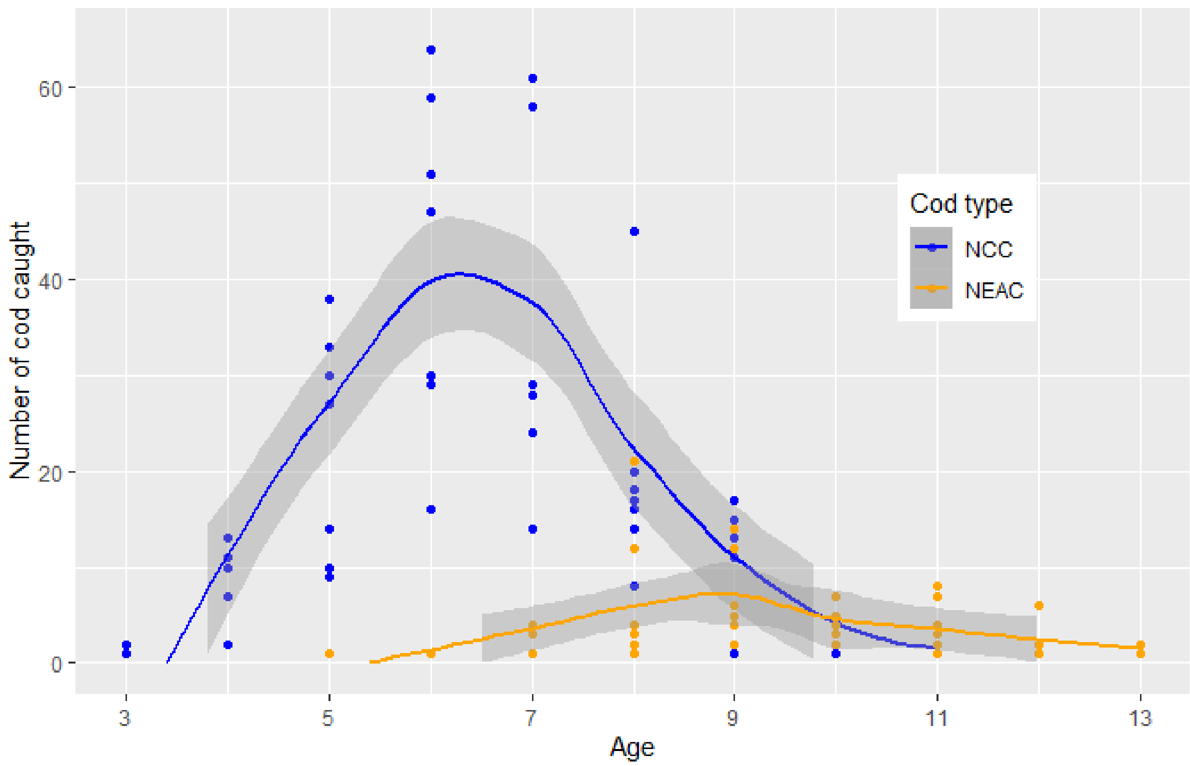

Figure 3.7: Age composition merged for all seasons for NC cod and NEA cod caught in Hessafjord. The lines are smoothed conditional means with confidence intervals (grey area surrounding the line) found in R using ggplot2.

3.1.3.2 Condition

The female NC cod had highest condition in 2015 and the lowest condition in 2018. The condition factor values did however not vary in a great extent (Table 3.7).

Table 3.7: Fulton's condition factor for the female NC cod in Hessafjord. The maturity stages are decided based on IMR's guidelines. Maturing and spawning fish are in stage 2 and 3, while spawned fish are in stage 4. All maturity stages imply stages 1 to 5.

Year	Condition including all maturity stages		Condition of maturing and spawning fish		Condition of spawned fish	
	Mean	*N*	*Mean*	*N*	*Mean*	*N*
2012	1.183	107	1.187	105	1.009	2
2013	1.240	50	1.240	50	-	0
2015	1.274	80	1.298	73	1.031	7
2016	1.160	88	1.190	77	0.951	11
2017	1.186	20	1.196	19	1.006	1
2018	1.089	45	1.141	34	0.834	7
2019	1.177	84	1.187	80	0.978	4

There was not a big difference in condition for female NC cod in maturity stages 2 and 3 from year to year (Figure 3.8). Running an ANOVA test followed by a post-hoc multiple comparisons test, done the same way as in equation 2.1 and 2.2, showed that there was not a significant difference in condition between most of the years. The year that stood out was 2015, with significant higher condition ($p < 0.05$) than the rest of the years, with an exception for 2017. 2013 and 2018 were also significant different from each other.

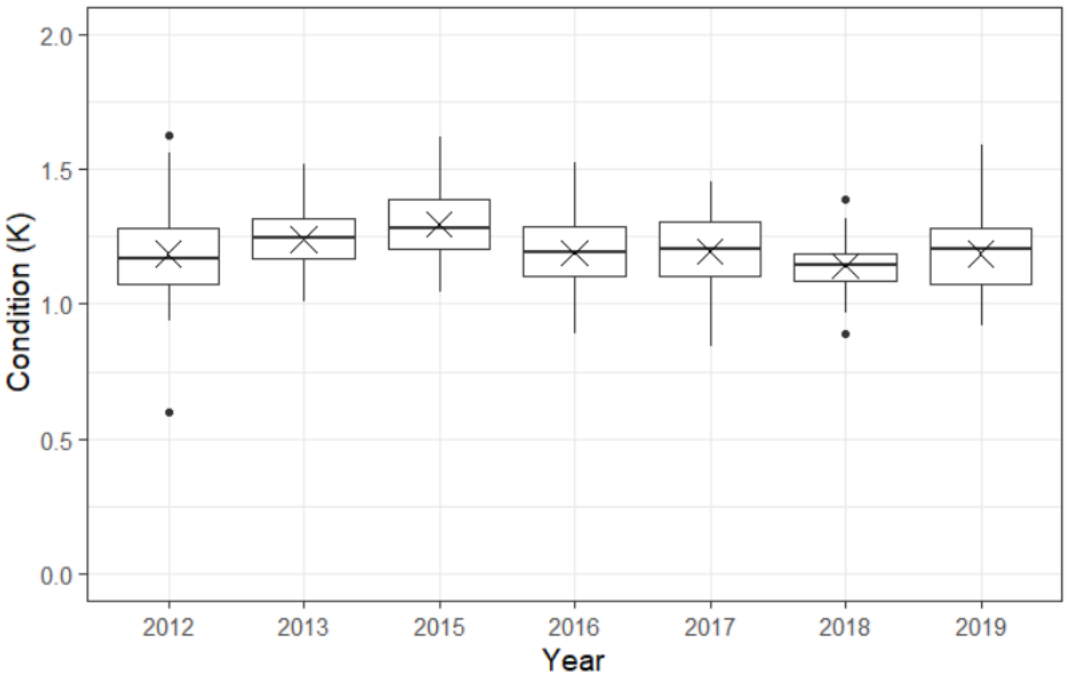

Figure 3.8: Boxplot showing estimated condition of female NC cod in maturity stages 2 and 3 caught in Hessafjord for each season. The cross shows the mean condition, the horizontal line shows the median (50th percentile), the box shows the 25th to 75th percentile, the vertical lines exiting the boxes shows the error bars, while the dots are outliers

3.1.3.3 *Mortality*

The mortality did not seem to drop from the years before the MPA implementation (1996 and 2002) to the years after the implementation (2012-2019), but rather it seemed to increase (Table 3.8). Figure 3.9 shows an example of estimated mortality rates based on a catch curve from 2012 (output from the example in equation 2.4 (chapter 2.2.3.3)).

Table 3.8: The estimated instantaneous (Z) and annual (A) mortality rates.

Year	1996	2002	2009	2012	2013	2015	2016	2017	2018	2019
A (%)	44.7	49.3	39.8	56.9	55.3	48.6	63.3	49.4	46.7	58.1
Z	0.59	0.68	0.51	0.84	0.80	0.67	1.00	0.68	0.63	0.87

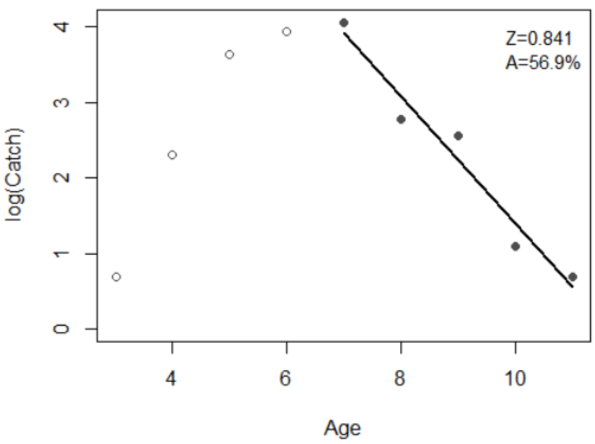

Figure 3.9: Mortality for Norwegian coastal cod in Borgundfjord based on NC cod caught in 2012. A is the estimated annual mortality rate, while Z is the estimated instantaneous mortality rate.

3.2 Modelled particle drift as proxy for egg drift

After 4 days, the proportion of eggs that were retained in the study area varied from 80 % to 86 % from year to year. An exception was in 2016, where it went down to 70 % retention. After 30 days, the proportion of retained eggs varied from 27 % to 33 % in the years from 2013 to 2017. In 2018 and 2019 the numbers were a bit higher, with 55 % and 45 % retained, respectively (Figure 3.10). Examples of the modelled egg distribution 4 and 30 days after a given date are shown in Figure 3.11.

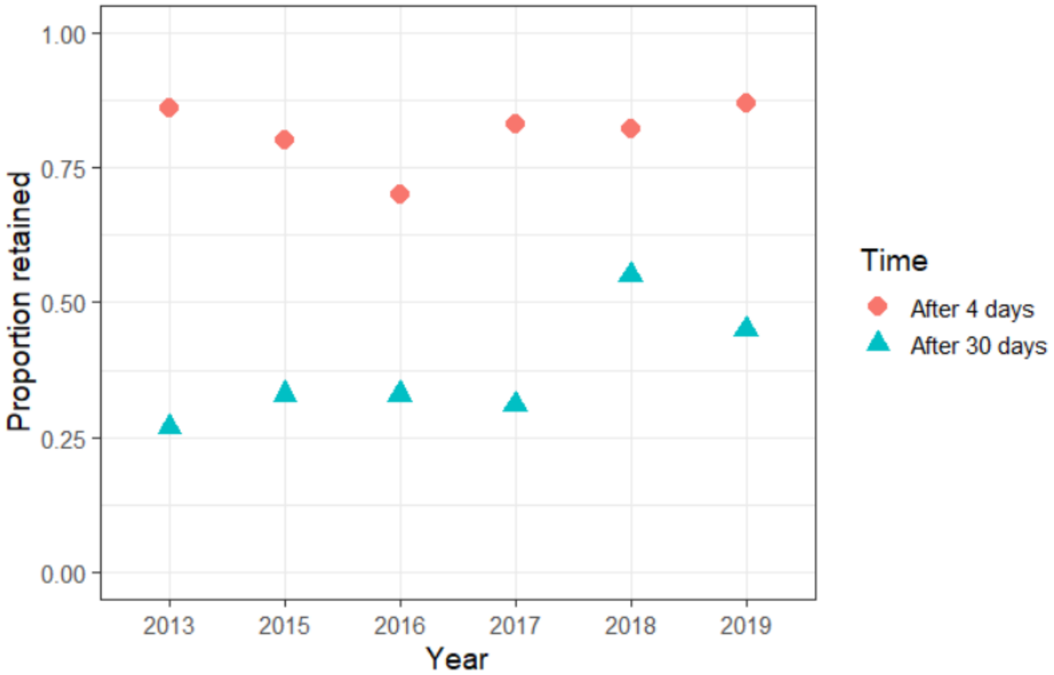

Figure 3.10: Weighted average of the proportion of eggs that were retained in the fjord in each year after 4 and 30 days.

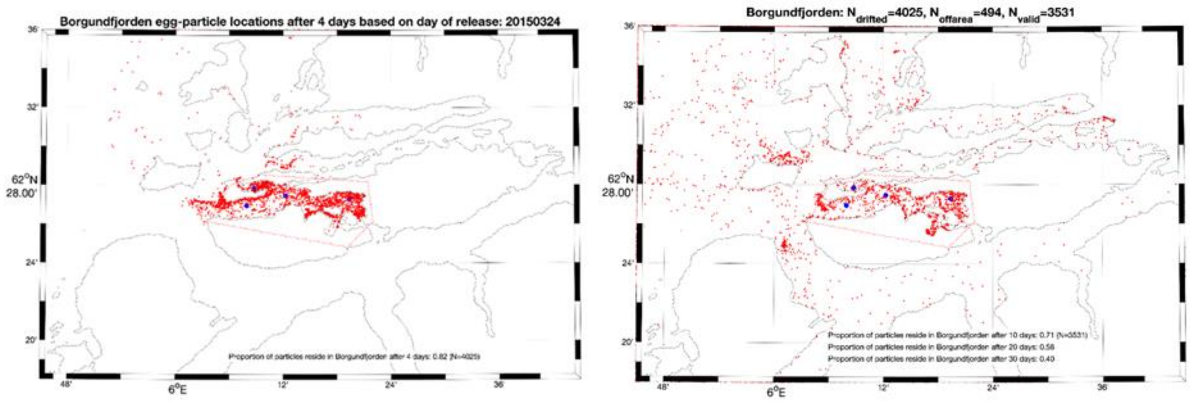

Figure 3.11: Example of a result of the modelled particle drift and the amount of eggs retained 4 (left) and 30 (right) days after a given date. Each dot represents an egg particle. In this case, 82 % of 4025 eggs were estimated to be retained inside the study area (red lines) 4 days after releasing the eggs on 24th March 2015, while 40 % were estimated to be retained after 30 days.

3.3 Total amount of NC cod and NEA cod eggs

3.3.1 Temperature's effect on egg development

An example of the use of temperature and the estimated amount of days for the egg to develop from stage 1 to stage 2 is shown in Table 3.9 (Eq. 2.6). The example shows the values used for Hessafjord in the spawning season of 2013. A mean temperature of 4°C gives a development time of approximately 4.5 days. As expected, colder temperatures increase the egg development time, while warmer temperatures decrease it.

Table 3.9: Example of values of temperature (T) used in equation 2.6 and the estimated amount of development days (D) at that temperature. These example values are the same as used for Hessafjord in 2013

Week	Mean temperature at 2-40 m depth (*T* in Eq. 2.6)	Days to end of stage 1B (*D* in Eq. 2.6)
9	3.9	4.6
11	4.4	4.4
12	4.3	4.4
13	3.9	4.6
14	3.8	4.7
15	3.9	4.6
16	3.9	4.6
18	4.9	4.1

3.3.2 NC cod to NEA cod relationship

An example of the estimated fraction of NC cod to NEA cod eggs (see chapter 2.4.4) is shown in Table 3.9. The example shows the fraction found for Hessafjord in the spawning season of 2013. All the weeks show a high fraction of NC cod eggs in the samples. Looking at the overall fraction of NC cod to NEA eggs, the lowest proportion was found in 2013, where 80 % of the eggs came from NC cod. 2016 and 2017 had the highest fraction of NC cod eggs, both with 95 % NC cod eggs in the samples (Table 3.11).

Table 3.10: Example of values found in the genetic analyses of the cod eggs, estimated using equation 2.6. This example shows the values for Hessafjord in 2013.

Week	Proportion coastal egg in Hessafjord 2013
9	1.00
11	0.50
12	0.65
13	0.71
14	0.87
15	0.97
16	1.00
18	1.00

Table 3.11: The overall proportion (weighted average) of NC cod eggs in the study area as identified by genetic analyses from year to year (see chapter 2.4.4).

Year	Overall proportion NC cod eggs
2012	0.84
2013	0.80
2015	0.90
2016	0.95
2017	0.95
2018	0.93
2019	0.93

3.3.3 Mean daily egg density with confidence interval

3.3.3.1 Mean daily egg density for NC cod

The year with the highest daily egg density (4.65 eggs/m^3/day) was 2013, while 2017 was the year with the lowest daily egg density (1.36 eggs/m^3/day). However, in 2013 the coefficient of variation $\left(\frac{S.E.}{\bar{x}_{NCC_{avg}}}\right)$ was approximately three times higher than the other years. This is reflected in the 95 % confidence interval, where the interval was larger for 2013 than the rest of the years. The spawning season, capsulated by the first and last day of egg sampling, usually lasted around 60 days. The shortest season was in 2012, when it lasted for 49 days (Table 3.12).

Table 3.12: Overview of estimated mean daily egg density (eggs/m^3/day) for NC cod, with the 95% confidence interval and the number of days covered. The variance of the season average, the coefficient of variation and the 2 times standard error are also listed.

Year	Number of days covered	Average daily egg density ($\bar{x}_{NCC_{avg}}$)	Variance of $\bar{x}_{NCC_{avg}}$	Coefficient of variation for $\bar{x}_{NCC_{avg}}$	2 x standard error for $\bar{x}_{NCC_{avg}}$	95 % confidence interval
2012	49	3.34	0.21	13.6%	0.92	(2.43, 4.26)
2013	62	4.65	2.31	32.7%	3.04	(1.61, 7.69)
2015	63	3.69	0.12	9.4%	0.69	(3.00, 4.39)
2016	63	2.51	0.054	9.3%	0.46	(2.04, 2.97)
2017	58	1.36	0.025	11.7%	0.32	(1.04, 1.67)
2018	63	2.68	0.067	9.6%	0.52	(2.17, 3.20)
2019	54	2.75	0.10	11.7%	0.64	(2.11, 3.40)

3.3.3.2 Mean daily egg density for NEA cod

The table for NEA cod shows the same trend as the corresponding table for NC cod regarding estimated mean daily egg density. Year 2013 had the highest density, while 2017 had the lowest density. The coefficient of variation was high for 2013, but also high for 2015, 2016 and 2017 (Table 3.13).

Table 3.13: Overview of estimated mean daily egg density (eggs/m^3/day) for NEA cod, with the 95% confidence interval and the number of days covered. The variance of the year average, the coefficient of variation and the 2 times standard error are also listed.

Year	Number of days covered	Average daily egg density ($\bar{x}_{NEAC_{avg}}$)	Variance of $\bar{x}_{NEAC_{avg}}$	Coefficient of variance for $\bar{x}_{NEAC_{avg}}$	2 x standard error for $\bar{x}_{NEAC_{avg}}$	95% confidence interval
2012	49	0.62	0.01	17.2%	0.21	(0.40, 0.83)
2013	62	1.16	0.13	31.5%	0.73	(0.43, 1.90)
2015	63	0.38	0.017	33.6%	0.26	(0.13, 0.64)
2016	63	0.14	0.0014	26.8%	0.074	(0.064, 0.21)
2017	58	0.07	0.00036	27.6%	0.038	(0.031, 0.11)
2018	63	0.17	0.00024	9.2%	0.031	(0.14, 0.20)
2019	54	0.20	0.00087	14.7%	0.059	(0.14, 0.26)

3.3.4 Total number of NC cod and NEA cod eggs

The total number of eggs followed the same trend as seen earlier. Year 2013 was estimated as the top year for both NC cod and NEA cod, while 2017 was the bottom year. The standard error was however high for 2013 (Table 3.14).

Table 3.14: Total number of NC cod and NEA cod eggs during the spawning season each year, with the 95 % confidence interval in parenthesis.

Year	Number of days covered	Volume of the fjord above 50 m (10^8 m^3)	Total number of NC cod egg (10^{10})	Total number of NEA cod egg (10^{10})
2012	49	4.98715	8.17 (∓2.24)	1.51 (∓0.52)
2013	62	4.98715	14.37 (∓9.41)	3.60 (∓2.27)
2015	63	4.98715	11.70 (∓2.18)	1.21 (∓0.81)
2016	63	4.98715	7.87 (∓1.46)	0.43 (∓0.23)
2017	58	4.98715	3.92 (∓0.92)	0.20 (∓0.11)
2018	63	4.98715	8.43 (∓1.62)	0.53 (∓0.10)
2019	54	4.98715	7.41 (∓1.73)	0.54 (∓0.16)

3.4 Spawning stock biomass

3.4.1 Fecundity estimates

For NC cod, the fecundity was highest in 2012 and lowest in 2013. For NEA cod, it was highest in 2015 and lowest in 2018. As expected, longer fish gave a higher fecundity, and the NC cod had a higher fecundity per length unit than NEA cod (Table 3.15).

Table 3.15: The estimated fecundities for NC cod (Eq. 2.11.1) and NEA cod (Eq. 2.11.2).

Year	NC cod		NEA cod	
	Mean length of females (cm)	Fecundity (10^6)	Mean length of females (cm)	Fecundity (10^6)
2012	90	5.13	96	4.52
2013	83	3.99	96	4.59
2015	86	4.47	101	5.97
2016	87	4.49	97	4.80
2017	87	4.56	97	4.85
2018	85	4.29	95	4.42
2019	87	4.57	97	4.90

3.4.2 Spawning stock biomass (SSB) for NC cod

The estimated SSB usually varied between 200 and 400 tonnes. The top year was 2013, which had an estimated SSB of 586 tonnes. That year did anyhow have a large uncertainty in the estimates, with a 95 % confidence interval ranging from 200 to almost 1000 tonnes. The bottom year was 2017, with 145 tonnes as the estimated SSB (Figure 3.12).

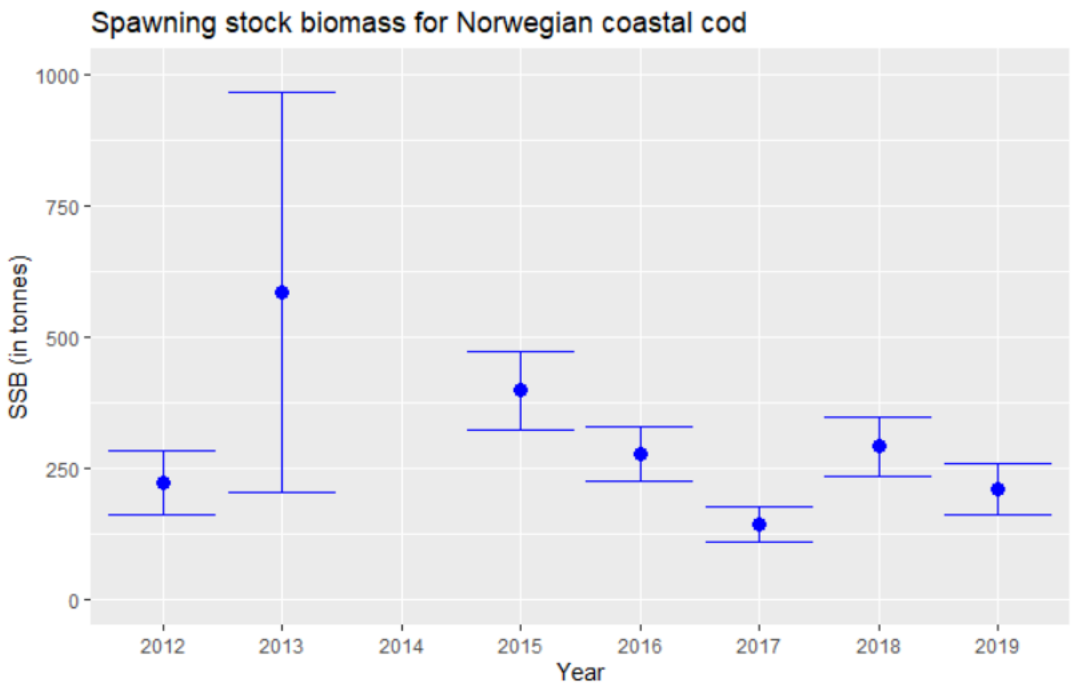

Figure 3.12: Estimated spawning stock biomass for NC cod with the 95% confidence intervals.

3.4.3 Spawning stock biomass (SSB) for NEA cod

The estimations for NEA cod also had 2013 as the top year and 2017 as the bottom year in the study area. In 2013 there was an estimated SSB of 161 tonnes, with a wide 95 % confidence interval ranging from 59 to 262 tonnes. In 2017, it was estimated that 10 tonnes of NEA cod entered the fjord to spawn. The other years ranges from approximately 15 to 60 tonnes (Figure 3.13).

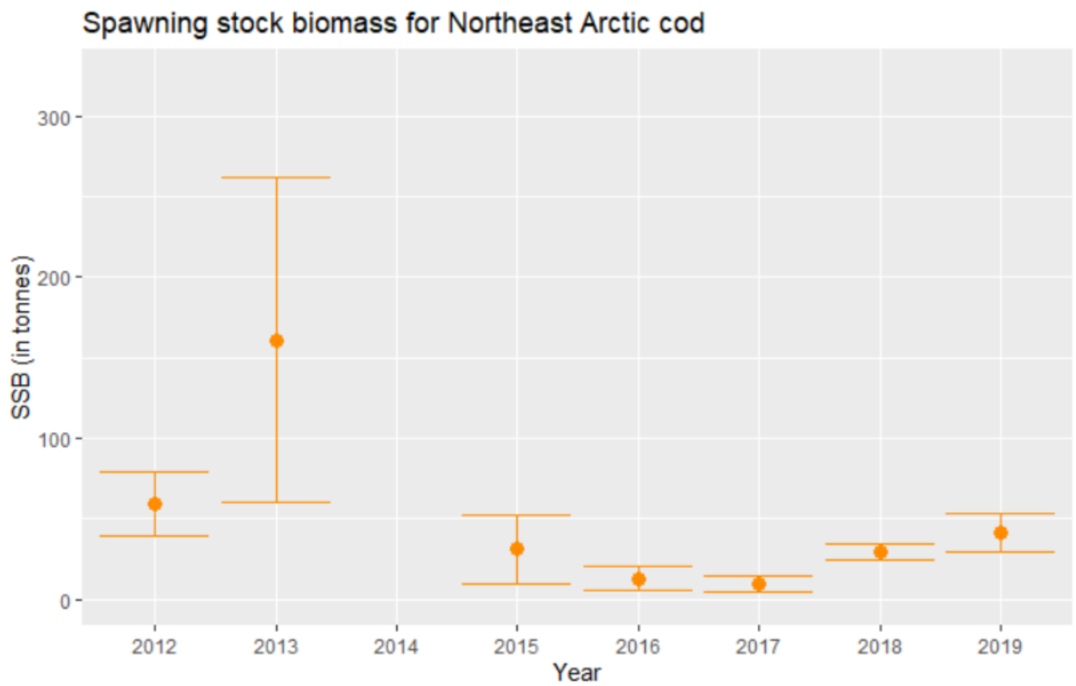

Figure 3.13: Estimated spawning stock biomass for NEA cod in tonnes, with the 95 % confidence intervals.

3.4.4 Uncertainties in length and weight

There were also uncertainties linked to the average weight and length used in the SSB estimates. There was not found a way to implement these uncertainties in the final SSB estimates (Figure 3.12 and Figure 3.13). The 95 % confidence intervals were instead calculated individually. Using the lower and upper end of the 95 % confidence interval showed that the SSB estimates for NC cod was not very sensitive for errors in the mean weight or length (Figure 3.14). The biggest difference came by changing the length in 2013. The reason why the lower end of the 95 % confidence interval regarding length gives a higher SSB, is that smaller fish have a lower fecundity. Hence, the average cod in the area spawn fewer eggs, which again means that more fish is required to spawn the amount of eggs found in the fjord.

Figure 3.14: Graphs showing how sensitive the SSB estimations for NC cod are for errors in the mean length of the female cod (left) and in the mean weight of both the males and the females (right). Lower shows the SSB estimate given that the lower end of the 95 % confidence interval for length or weight is used. Upper shows the SSB estimate given that the upper end of the 95 % confidence interval is used. Standard is the SSB estimate if the calculated mean weight and length is used. Notice that the 95 % confidence interval for length or weight is from upper point estimate to lower point estimate within each year.

The SSB estimates for NEA cod did not show any major differences when using the lower and upper end of the 95 % confidence interval for length or weight (Figure 3.15). The exception is the change in length in 2013, where the point estimate varied from 120 tonnes to approximately 210 tonnes, depending on the length used. The change in weight in 2013 affected the SSB to some degree.

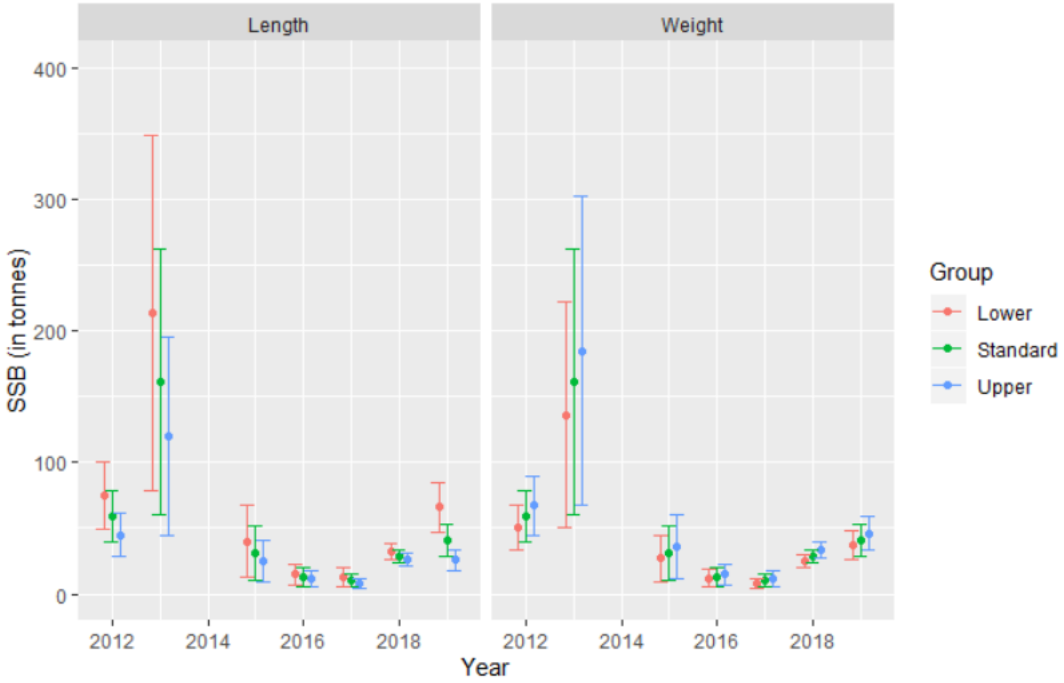

Figure 3.15: Graphs showing how sensitive the SSB estimations for NEA cod are for errors in the a) mean length of female cod (left) and mean weight of both males and females (right). Lower shows the SSB estimate given that the lower end of the 95 % confidence interval for length or weight is used. Upper shows the SSB estimate given that the upper end of the 95 % confidence interval is used. Standard is the SSB estimate if the mean weight and length is used. Notice that the 95 % confidence interval for length or weight is from upper point estimate to lower point estimate within each year.

4 Discussion

In the present study the spawning stock biomass of cod in Borgundfjord has been estimated from the years 2012 – 2019 (excl. 2014). This was done using net hauls performed during the spawning season, where genetic analyses, sea temperature and data from cod landings in Hessafjord have been included in the estimates. Different factors, both abiotic and biotic, have been investigated to see what could have caused the fluctuations in the SSB estimates from year to year.

The results suggest that the MPA has not led to an increase in coastal cod spawning. The estimated SSB of NC cod varied from 145 tonnes (2017) at the lowest to 586 tonnes (2013) at the highest. The second highest estimated SSB for the NC cod was in 2015, when the spawning biomass was around 400 tonnes. Estimated SSB was between 200 and 300 tonnes for the remaining years (Figure 3.12). Even though 2013 was estimated as the top year, the 95 % confidence interval show a great uncertainty in the result, with an interval ranging from 203 to 970 tonnes. This uncertainty was caused by large variation in the amount of eggs between areas during the top spawning weeks, where Aspevåg stood out with a very high amount of eggs (Figure 3.1). For NEA cod, the lowest estimated spawning stock biomass (SSB) during the study period was at 10 tonnes in 2017, while the highest estimated SSB was 189 tonnes in 2013, also here with a wide 95 % confidence interval. In 2012 the biomass was estimated to about 90 tonnes, but since 2015 the estimated SSB has not exceeded 50 tonnes (Figure 3.13).

4.1 What causes the fluctuations in the SSB estimates between the years?

Fluctuations in fish stock biomass is caused by growth, recruitment, immigration, emigration, natural mortality and fishing mortality. The former three increase the stock biomass, while the latter three decrease it. Hence, for the biomass to increase, growth, immigration and recruitment have had to be higher than mortality and emigration, and opposite for the biomass to decrease. These factors are often affected by environmental anomalies, years with very high or low recruitment, inter- and intraspesific interactions, and fishery (Laevastu & Marasco, 1982). Immigration, emigration and recruitment have not been investigated in this study, and their impact on the fluctuations is difficult to assess. The mortality has however been estimated (Table 3.8 and Appendix V), which showed to be high throughout the study years, but there did not seem to be any pattern between the estimated mortalities and the estimated SSBs.

The factors mentioned above impact the actual biomass, but there could however be other reasons than an actual change in biomass to why the SSB estimations fluctuate from year to year. Years with fewer cod eggs often had fewer eggs from other species as well, and vice versa at years with more cod eggs (R^2 = 0.65, Figure 3.3). Hence, the intensity of spawning in the area somewhat corresponded across species, indicating that there were other factors leading to increased or decreased spawning and/or amount of eggs in samples, regardless of species. Therefore, I have looked at different factors which might affect the amount of eggs in the net hauls and the final SSB estimations, among them hydrography, particle drift and NC cod female condition.

4.1.1 Hydrography

The temperature and salinity at the study areas have been measured each study year (Appendix III and IV). Cod prefer to spawn at temperature between 4°C to 7°C (González-Irusta & Wright, 2016; Yaragina et al., 2011). Each season had temperatures which were in this interval, but the two years that stood out in terms of temperature, were 2013 and 2018, where the temperature was approximately 2°C colder than the other years (Figure 3.5). These were also two of the three years with most cod eggs (Figure 3.1 and Table 3.2), which might indicate that lower temperatures give higher egg densities. However, lower temperature gives slower development, which could explain why there are more stage 1 eggs, as they have had more time to aggregate. If this is the only reason for why cold years had more eggs, then it has been accounted for by estimating the egg development time at given temperatures (Eq. 2.6). When it comes to salinity, there does not seem to be any obvious connection between the salinity and the egg densities in Borgundfjord during the study years (Figure 3.4, Figure 3.1 and Appendix IV). And as discussed later in chapter 4.3.1.1 the salinity should not have hampered the vertical buoyancy of the eggs, and hence not the egg development and egg density in the upper 50 m of the water column.

4.1.2 Particle drift

The particle drift simulation was used to see if there were differences in the currents between the years that could affect the amount of eggs retained in the fjord and hence in the samples. The idea behind testing this was to check if there was a high drift of eggs out of the area in the years with few eggs, and vice versa at years with many eggs. Based on the result from these simulations, there was no clear pattern between the drift out and the amount of eggs in the samples (Figure 3.10 and Table 3.2). If egg drift out of the area, where they are unavailable for the net hauls was the big driver behind the fluctuations in the SSB estimates, then year

2017 should have a low retention of eggs and 2013 should have a high retention. This is not the case, as 2017 and 2013 after four days have a weighted average of eggs retained in the fjord of 83 % and 86 %, respectively. 2013 also had a high amount of eggs in one of the study areas (Aspevåg, Figure 3.1), possibly caused by a high retention of eggs compared to the other years and areas. The particle drift simulations show that this is probably not the case (Figure 3.10 and Appendix VII, Table 6.2). Hence, there must be something else causing the fluctuations.

4.1.3 Condition

The only year that differed from the other years in condition of the female cod, was 2015 (Figure 3.8). The female NC cod that year had a slightly higher condition, which could have caused a slightly higher fecundity and amount of eggs in the fjord. However, the general lack of significant difference from year to year, indicates that condition and food availability are not the driver behind the SSB fluctuations either.

4.1.4 Could they spawn elsewhere?

It can be hypothesized that the cod, for unknown reasons, could spawn in Ellingsøyfjord or somewhere else than in the study area. The spawning in Ellingsøyfjord follows the same trend as in Borgundfjord, where the spawning intensity follows a bell shaped with a peak in the middle of the season (Appendix I). However, the variation in amount of eggs between the years is not similar. An example is that relatively many eggs were found in Ellingsøyfjord in 2016, when there were relatively few eggs in Borgundfjord. This could indicate that that year, a bigger fraction of the cod had spawned in Ellingsøyfjord instead. To what extent this has happened, is not certain.

4.1.5 Estimations of SSB of NC cod in Borgundfjord versus SSB of NC cod from 62°N and northwards

No matter what has caused the fluctuations of NC cod in Borgundfjord, there are some indications that it has affected the NC cod in general as well. During the study years in Borgundfjord, ICES has also estimated the NC cod SSB from 62°N and northwards to the Russian border based on a trawl-acoustic survey (ICES, 2019a), and the ICES estimates and the point estimates from this study seem to follow a similar trend (Figure 4.1: SSB estimates for NC cod from this study and SSB estimates for NC cod from trawl-acoustic surveys performed by ICES (ICES, 2019a) show conformity.Figure 4.1). This could fit simply by chance, but it might also indicate that the fluctuations we observe in Borgundfjord follow the dynamics of the combined Norwegian coastal cod population, rather than the fluctuations being caused by random stochasticity or flaws in estimation or method.

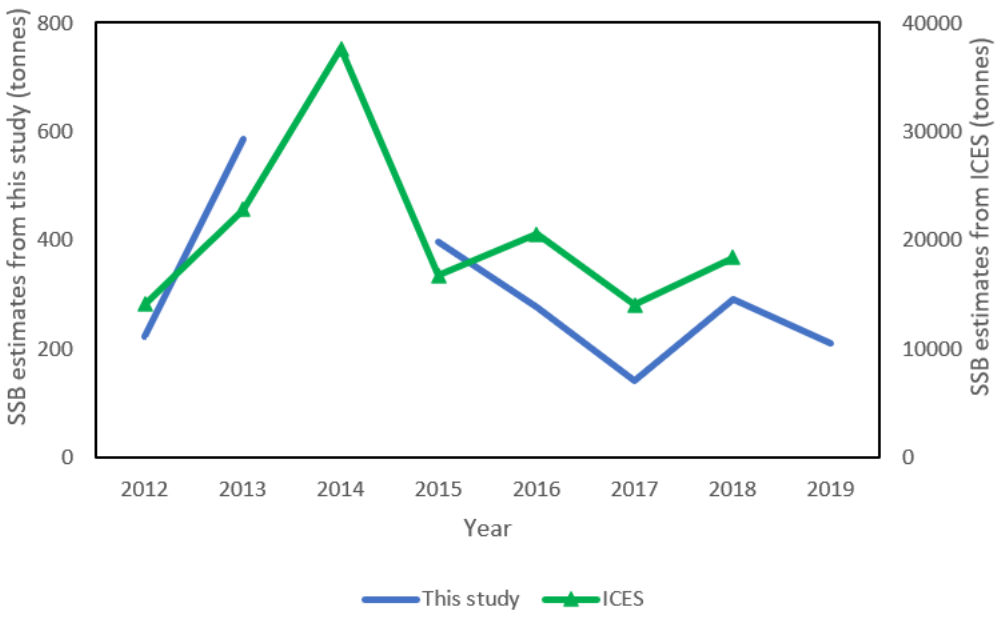

Figure 4.1: SSB estimates for NC cod from this study and SSB estimates for NC cod from trawl-acoustic surveys performed by ICES (ICES, 2019a) *show conformity.*

4.2 Has the MPA been successful?

The reason for starting sampling after the MPA introduction, was to get an indication of its effect, and to see if there should be introduced further measures to protect the coastal cod. Based on the results in this study, there do not seem to be any obvious improvement in the NC cod stock as a result of the MPA implementation (Figure 3.12). Hence, if the aim of the MPA was to increase the SSB in Borgundfjord, it has not been successful as it has not led to that. The situation for the NC cod stock may however have been worse before the introduction of the MPA, and that there has been a sudden improvement in the stock from 2009 to 2012, before it now in later years has somewhat stabilized at around 200 to 300 tonnes. This is however difficult to assess, as data were not gathered before 2012, three years after the MPA implementation in 2009. In addition to the possibility of a sudden increase in SSB from 2009 to 2012, it is also a possibility that without the MPA, the SSB had declined a lot due to other factors than fishing (like predators, temperature and food availability), but that the MPA has somewhat buffered for that.

MPAs could serve as a protection for older and larger individuals, and in that way reduce the ecological and evolutionary effects of harvesting (Fernández-Chacón et al., 2020). The fishing mortality of spawning cod in the area has most likely been lower than it would be otherwise, as there has been no commercial harvesting or net fishing in the MPA during the spawning season from 2009 until present. A decreased fishing pressure has shown to lead to an increase in abundance and larger fish (Alós & Arlinghaus, 2013), as well as being beneficial for a fish population as both mortality and disturbance are reduced (Grüss, Kaplan, & Robinson, 2014; Morgan, Deblois, & Rose, 1997). A similar ban as in Borgundfjord, allowing only hook and line fishery, also increased the survival of the cod along the Skagerrak coast by a substantial amount (Fernández-Chacón et al., 2015). However, looking at the SSB estimations and the mean lengths and weights of the NC cod in this study, the cod does not seem to have become larger or more abundant (Table 3.5 and Figure 3.12). Neither does the total mortality seem to have gone down, but rather it seems to have increased (Table 3.8). Lastly, looking at the age distributions, the amount of older fish does not seem to have gone up either (Figure 3.6). Hence, the benefits with MPAs shown in other studies do not seem to apply to the cod in Borgundfjord, other than what could be a reduced disturbance and fishing mortality.

4.2.1 Why haven't we observed an increase in the SSB?

Inadequacy of design and failure of implementation has been seen as two main reasons to why MPAs are ineffective (Spalding et al., 2016). Failure of implementation often happens when the reserves are managed in a bad way or have little resources, so that the people using the area do not even know about the existence of the reserve. The restrictions regarding the Borgundfjord MPA have been much discussed both in media and otherwise, and it is not likely that local people do not know about its existence. The fishery has also been supervised by the Directorate of Fisheries for several of the seasons. Hence, it is not likely that there has been any failure of implementation, but has there been inadequacy of design? Lowering the fishing pressure is important, and lack of this is one of the main causes for the decline in the NC cod stock population (ICES, 2019a). This has been done in Borgundfjord by banning commercial fishing and fishing with net, but only in parts of the spawning area, and recreational angling fishery is still allowed. The recreational fishing on cod might however be higher than commercial fisheries. Nine years of tag-recovery data of NC cod on the Skagerrak coast showed that recreational fishing accounted for ~70 % of the total cod catches, where rod and line fishing had the biggest impact (Kleiven et al., 2016). In the Borgundfjord MPA, the mortality seems to rather have gone up since before the MPA introduction (Table 3.8). Hence, even though the commercial fisheries have been banned during the spawning season, the fishing pressure may still be too high to increase the stock population. Thus, the bans in Borgundfjord may not be enough to increase the stock.

After a collapse, only a few fish populations have recovered rapidly (Hutchings & Reynolds, 2004). This could be caused by the Allee effect, which implies that the population growth per capita declines when the population abundance is below a certain threshold. Increased natural mortality, change in predator-prey interactions and failure of reversal of fisheries induced evolution could all be examples of why the recovery may be slow (Swain, 2011). Even though the NC cod stock in Borgundfjord necessarily has not collapsed, the slow recovery might be affected by some of the same factors.

4.3 Limitations with method and uncertainties of result.

When doing an estimation with this many factors, there could be several limitations and/or uncertainties to the method used. Errors could have been caused by flaws with the sampling design, and errors could have occurred at data collection stage or the estimation stage.

4.3.1 Potential flaws with sampling design

4.3.1.1 Are the hauls taken deep enough?

The net hauls have been performed from 50 metres and up, and there has hence not been sampling for eggs deeper than this. This leaves us with the question whether there could be eggs lower in the water column or not. If that is the case, and a great amount of eggs have been missed in the data gathering, the results in this thesis would underestimate the SSB. However, investigations on the egg specific gravity for three NC cod populations, showed that the mean egg specific gravity (when transformed into salinity unit at 6°C) of these populations varied from 30.4 to 31.2 ppt (Jung et al., 2012). The batch with the highest value was found to have an egg specific gravity at 32.7 ppt. Egg specific gravity is a function of egg volume, chorion volume, perivitelline space (PVS) and the specific gravity of chorion and ovoplasm (Kjesbu et al., 1992). Eggs have a neutral buoyancy where the egg specific gravity of the egg corresponds to that of the ambient water, meaning that the eggs will float up until it reaches water with similar specific gravity. Looking at the salinity profiles (Appendix IV), the salinity was rarely lower than 33 ppt at 40 m in the Borgundfjord area, meaning that eggs would have floated freely up to the net haul interval (0-50 m depth) where the salinity is lower than 33 ppt.

In addition, cod eggs have a neutral buoyancy approximately at sea-water density σ_t= 24 (Kjesbu et al., 1992). For eggs to float up, the σ_t of the surrounding water has to be higher than 24. Typically, the temperature and salinity at 40 metres in the study areas were at 6°C and 33-34 ppt, respectively (Appendix III and IV). Estimating the σ_t for water at 40 metres depth with a temperature at 7°C and salinity at 33 ppt, gives a value of σ_t at ~26. The upper end of the temperature measurements (7°C) and the lower end of the salinity measurements (33 ppt) was chosen to be on the safe side, as colder and more saline water is heavier than warmer and less saline water. This taken into consideration, eggs spawned deeper than 50 m would have floated up into the net haul interval, making it unlikely that a great amount of eggs have been missed in the data gathering as a consequence of the chosen depth interval. As NEA cod has a similar to lower egg specific gravity, it is not likely that a great amount of their eggs have been missed either.

According to Godø (1977) the best catch rates of cod in the Borgundfjord used to be at 50-70 m depth. It is, however, not unusual for the NC cod in the study area (Figure 1.1) to stay at 30-40 m depth when spawning (fisher Jan Audun Wiik, pers. comm.). This means that even newly spawned eggs are found in the net haul interval. It is further assumed that the NEA cod stay deeper than the NC cod and down to 60 – 90 m. Eggs spawned at these depths might then be a bit older when they enter the net haul depth interval, and some may hence be missed in the sampling. For the future, it would be useful to document the differences in the spawning depths for the two cod types.

4.3.1.2 Were there enough replication and randomisation in the sampling?

Randomisation and replication are important to get precision and accuracy when planning a survey design. Randomisation implies that each object in the population would have the same chance of being sampled, hence avoiding bias and enhancing accuracy. The problem regarding randomisation is selectivity of the sampling gear. Replication is important to reduce the variability of the results, and in that way get more precise results. The problems regarding replication are costs and capacity.

Replication and randomisation of egg samples

Randomisation is likely not a problem regarding the egg sampling, as every egg has the same chance of getting caught (given that the retention of the net is 100 %). Here, the replication was seen as a bigger problem, as some years showed a high coefficient of variation indicating a rather low precision. This was a bigger problem for NEA cod than for NC cod, as for NEA cod three of the study years had a coefficient of variation at around 30 % (Table 3.13), while for NC cod only 2013 had a rather high coefficient of variation (Table 3.12). However, the rest of the study years had acceptable values for the coefficient of variation.

Replication and randomisation of cod landings

To achieve randomisation, all the fish should have the same chance of getting caught. However, gear parameters, soak time, fish behaviour and environmental conditions, amongst other parameters, could all affect the selectivity of a gill net (Holst et al., 2005). As a result of this, there are no fishing gears that exhibit no selectivity (Salvanes, 1991). Gill nets are selective, and this selectivity may bias the estimates of both the population size (Figure 3.12 and Figure 3.13) and mortality rates (Table 3.8) (Jensen, 1981). Hence, it cannot be excluded that selectivity also has occurred in the cod sampling in Hessafjord.

Also, Hessafjord is the only place allowed to fish with net, and it could be that the cod in Hessafjord has another composition of age, weight, length and sex than the cod in the rest of the study area. An example of this is that the net catches in Hessafjord showed a more than twice as high proportion of NEA cod than what the egg genetics showed (Johansen et al., 2017). This could be a result of some NEA cod coming to the area, but leaving without having spawned in Borgundfjord, or that coastal cod is less susceptible to the net than the NEA cod (e.g., by choosing another route into the fjord).

The sampling size (replication), enhancing precision, seems to be large enough, as the uncertainty estimates of length and weight showed a rather low impact on the final estimates (Figure 3.14 and Figure 3.15). An exception is for amount of NEA cod caught in 2017, where only five fish were caught (Table 3.6).

4.3.2 Data collection errors

The first collection error could have occurred already at the net hauls. The retention of the WP2 hand net might not have been 100%, or some eggs could have slipped out during the haul. When the eggs from the net were gathered, the net was flushed to get all the eggs down to the cod-end. There could also have occurred errors here, as some eggs may not have been flushed off from the net and into the cod-end. Further, the samples have sometimes been split in 2 or 4, to lessen the amount of egg counting. When doing this, the eggs may not have been evenly distributed in the plankton splitter. Errors could also have occurred when separating the eggs into species, when separating them into stages, or when counting them. These collections have however been conducted by experienced people, and the sampling has been performed the same way each year. Hence, it is not seen as a potentially large source of error, and no errors regarding the egg collections were taken into account in the estimations.

4.3.3 Errors at the estimation stage

4.3.3.1 Fecundity estimates

Hunter & Lo (1993) described fecundity estimates as the Achilles heel in ichthyoplankton-based biomass estimations, but knowledge of fecundity processes has increased substantially since this (Armstrong & Witthames, 2012). In this study, the length-fecundity function is based on an estimate with R^2 at 0.5 (Appendix VIIIa). This implies a quite big variation in the relationship between length and potential fecundity for the NC cod in Borgundfjord, making the final fecundity estimates (Table 3.15) somewhat uncertain.

4.3.3.2 Implementing temperature's effect on egg development.

The idea behind implementing the temperature's effect on the egg development was to estimate a time window of when the stage 1 eggs collected in the net hauls could have been spawned (lower temperatures translated into slower development and this gave longer time window for an egg to be included in the calculations). However, during this time, i.e. the time from spawning of the oldest stage 1 eggs to the time of the net haul, both mortality and drift out of the area could have affected the egg abundance. To compensate for the loss of eggs, in addition to get close to an average age of the stage 1 eggs, it was decided to divide the number of days by 2 (Eq. 2.8.1 and Eq. 2.8.2). Hence, it was assumed that the egg abundance *with* egg loss during this time window corresponded to egg abundance *without* egg loss during half of the time window. The losses due to egg mortality and particle drift seemed to be somewhat even throughout the years (Table 3.1 and Figure 3.10), making it reasonable to use the same compensation number for the different years. The choice of dividing the number of days by 2 to compensate for egg losses and getting close to an average age of the stage 1 eggs, was however only a rough "guesstimate". The number chosen to divide the number of days was quite important, as the final estimates changed proportionally with that number. Thus, the SSB estimates doubled when dividing it by two, tripled when dividing it by three, and so on.

There are also some uncertainties linked to the temperatures used for the egg development time (Table 3.9): (i) the temperature may have varied from the time of the oldest stage 1 eggs were spawned to the time of the egg sampling, for example between night and day; (ii) the temperature varied with depth, and the eggs could have experienced different temperatures, depending on how they were distributed in the water column; (iii) eggs could have drifted from an area with a different temperature. Unless the eggs have experienced big differences in the temperature, these uncertainties are not thought to have had a major impact on the results.

4.3.3.3 *Uncertainties in weight and length data*

There were also uncertainties linked to the average weight and length used in the SSB estimates. There was however not found a way to implement these uncertainties in the final SSB estimates (Figure 3.12 and Figure 3.13). Instead, this was instead calculated individually, which is shown in Figure 3.14 for NC cod and Figure 3.15 for NEA cod (the uncertainties are shown in the parenthesises in Table 3.5 and Table 3.6). These uncertainties did not have a big impact on the NC cod estimates, other than the uncertainty in length in 2013. For NEA cod, the impact was somewhat higher, especially regarding uncertainty in length in 2013.

4.3.3.4 *Fraction of NEA cod eggs*

The answer could sometimes be negative when estimating the fraction of NEA cod eggs (Eq. 2.7), indicating a negative fraction of NEA cod eggs. This happened when the α was higher than the observed fraction of Pan I^B alleles ($fractionB$, Eq. 2.7) from the genetic analysis. A negative fraction is obviously not correct, as it is not possible that there is a negative amount of NEA cod eggs. Therefore, in the cases where this happened, the fraction of NEA cod eggs was set to zero.

4.3.3.5 *Catch curves and mortality estimates*

When estimating the mortality based on cross-sectional catch-curves some assumptions should be met, as explained in chapter 2.2.3.3 (Table 3.8 and Appendix V). This includes constant recruitment and constant vulnerability to the fishing gear independent of year and age. The descending right limb of the catch curves (Figure 3.9 and Appendix V) is likely caused by mainly mortality, but it could also have been affected by selectivity of gill nets, making older fish underrepresented in the landings. Selectivity of the gill nets are thus likely to have caused differential vulnerability to be caught. In addition, it is unlikely that there has been constant recruitment to the fishery. Based on this, the results from the mortality estimates need to be handled with caution. For later research, it would be interesting to estimate the mortality more thoroughly and get more certain estimates of how the mortality have changed from before versus after the MPA implementation.

4.3.4 Do the data collected allow for judgement on whether the introduction of the MPA protects the NC cod in a satisfactory manner

As discussed above, there are some uncertainties related to this method, were the fecundity estimates and the choice of dividing the amount of days by 2 in equation 2.8.1 seem to be most prominent. The choice of dividing by 2 was decisive, as how high or low the SSB was estimated to be, was highly dependent on that number. Also, selectivity of the gill nets could have biased the population estimates (Figure 3.12 and Figure 3.13), mortality estimates (Table 3.8), and the mean weight and length (Table 3.5 and Table 3.6) used in the SSB estimates. The effect the potential selectivity could have had on the final biomass estimates, has not been investigated. There do, however, not seem to be any reason to doubt the trend of the estimates, which shows no obvious increase in spawning stock biomass.

When introducing a MPA, one should also consider the objectives, e.g. a certain increase in SSB or an increase in proportion of older age classes. This MPA does not, to my knowledge, have any other objective than to protect the coastal cod. Secondly, when assessing a MPA it is important to have a plan for how to measure its effect. Before-after-control-impact (BACI) analysis is a tool with a simple and robust design for evaluating the effects of a MPA (Kerr et al., 2019), but that analysis requires data from before the MPA implementation. In this study, the data collection did not start until three years after, making it difficult to assess its effect. However, if protecting the NC cod in a satisfactory manner implies increasing the SSB and the proportion of older age classes in the years after the MPA, then it seems safe to say it has not been the case.

4.4 Conclusion

This thesis shows that it is possible to estimate the spawning stock biomass of cod in the Borgundfjord for the time series available (2012-2019, excluding 2014). The estimations varied from year to year, with a SSB usually between 200-400 tonnes. Year 2013 was estimated as the top year SSB-wise (although with a high uncertainty in the estimate), and 2017 as the bottom year. To ensure the quality of the estimations, different sources to what might have caused the fluctuations, other than actual change in biomass itself, was checked. Environmental conditions that were checked includes sea currents, hydrography and condition of the fish. None of these seem to be the driver behind the fluctuations. Thus, it seems as the SSB fluctuations are caused by change in the actual SSB, and that the trends shown in the estimations (Figure 3.12 and Figure 3.13) are real. The lack of an obvious increase in the SSB estimates and in the proportion of older age classes, in addition to no drop in mortality, indicate that the MPA has not had the wanted effect. The ban of commercial fishing and gillnet fishing has nevertheless likely reduced the fishing pressure, even though the total mortality does not seem to have dropped. Reducing the fishing pressure is important as NC cod is a vulnerable stock, and a large proportion of the cod in the area is coastal cod.

This study describes a standardized way of estimating the spawning stock biomass based on egg data, which can be used in other MPAs and areas of interest. For later research, it is recommended to find a better way to compensate for egg loss of the stage 1 eggs from the time of spawning to the time of sampling. In addition, it is recommended to estimate the mortality from before and after the MPA implementation in a more thorough way, and in that way be more certain of how the mortality has developed.

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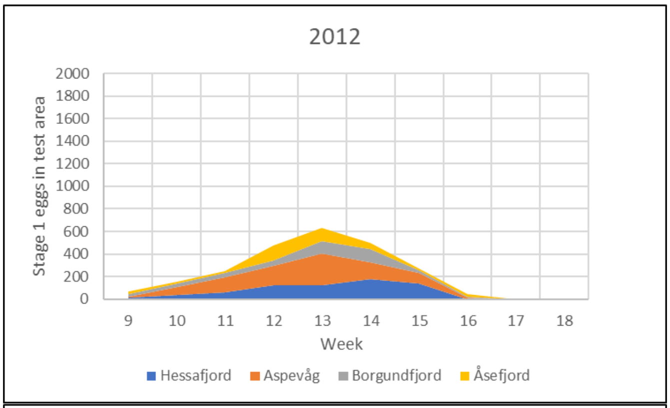
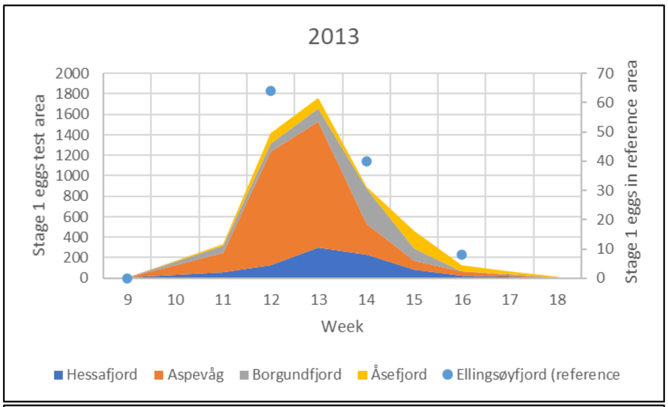
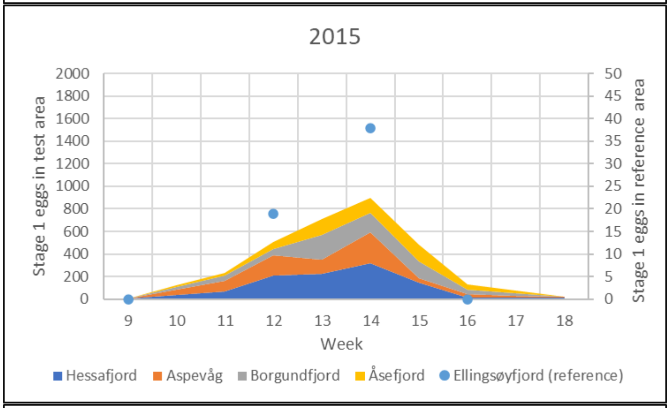
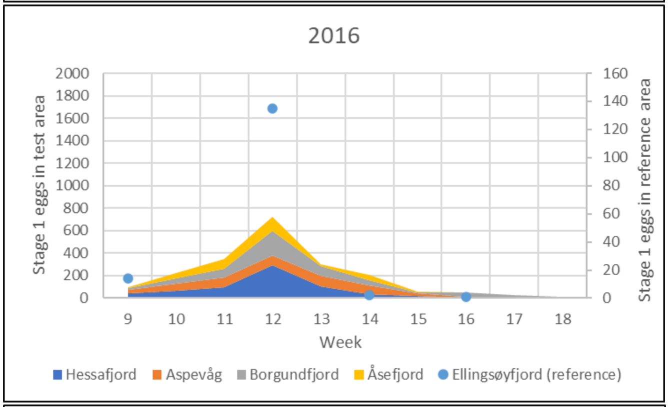
6 Appendices

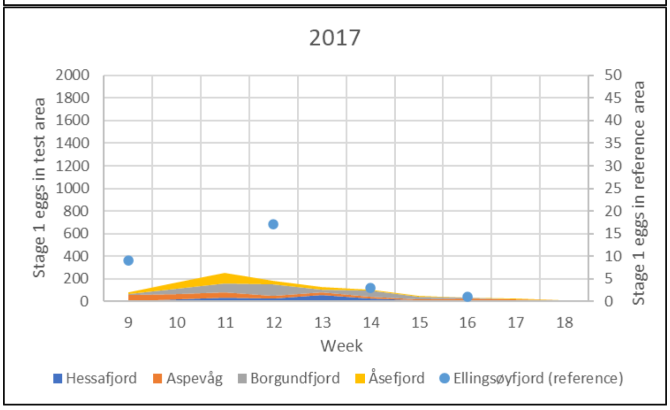
6.1 Appendix I: *Total amount of stage 1 eggs from 2012-2019 (minus 2014), including Ellingsøyfjord (reference area), minus 2012, on the y-axis to the right*

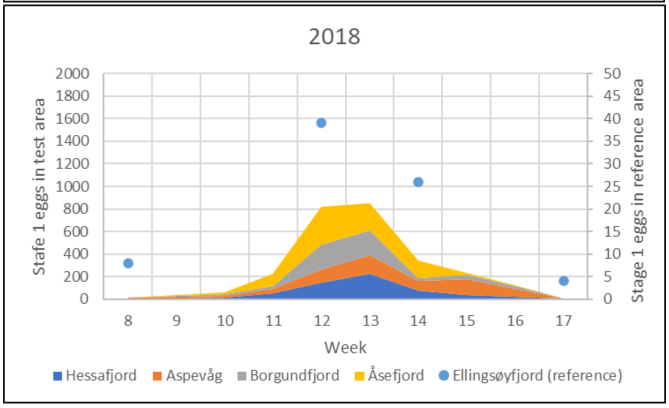


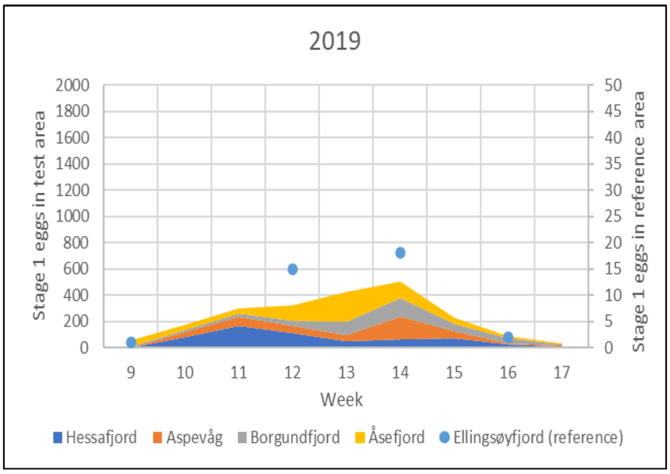












6.2 Appendix II: *Deciding the development stages of the cod eggs*

1. Fra de første celledelingene til rund kimskive. Kan inndeles videre etter antall synlige celler (0,2, 4, 8 eller flere). Dette kan skrives som 1,0 – 1,2 – 1,4 – 1,8 – 1,9

2. Fra fosteret begynner å dannes til det dekker ca halve egget.

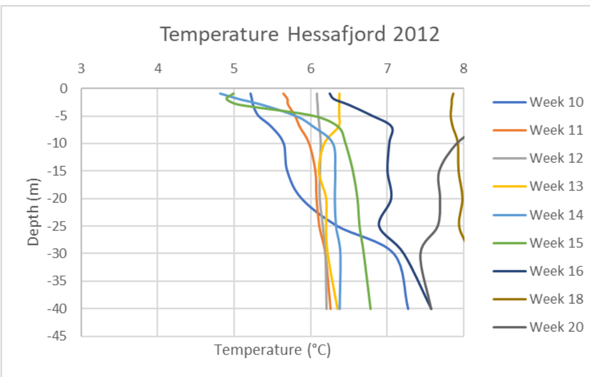
3. Fosteret dekker ca ½ til ¾ av egget. Øynene begynner å bli synlige, pigment på halen dannes.

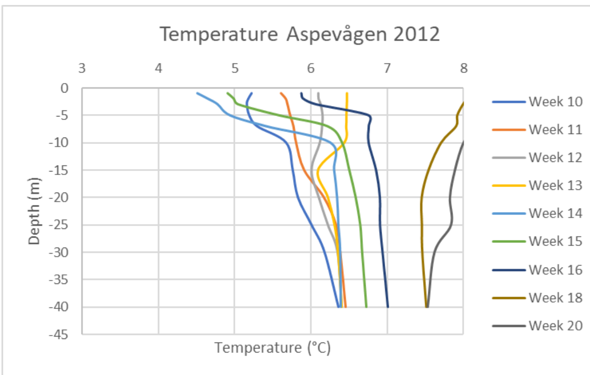
4. Fosteret går rundt hele egget. Mer spredt pigment på halen dannes.

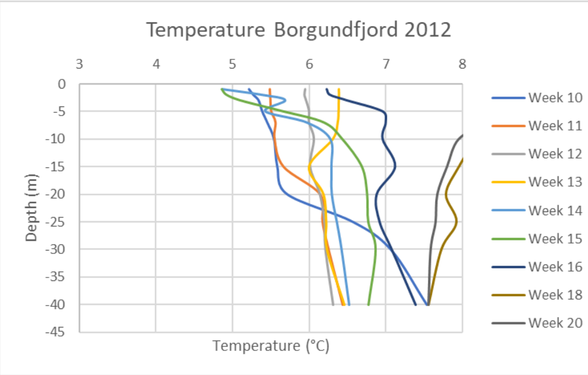
5. Halen vokser forbi hodet. Øynene pigmenteres, og pigmentbånd på halen blir tydelige.

Figure 6.1: The different stages of cod egg development. Everything, except the subdivisoning of stage 1 eggs, is retrieved from Thompson & Riley (1981)

6.3 Appendix III: *Temperature profiles for 2012-2019, minus 2014*






Temperature Borgundfjord 2012
3 4 5 6 7 8
0 -5 -10 -15 -20 -25 -30 -35 -40 -45
Depth (m)
Temperature (°C)
Week 10
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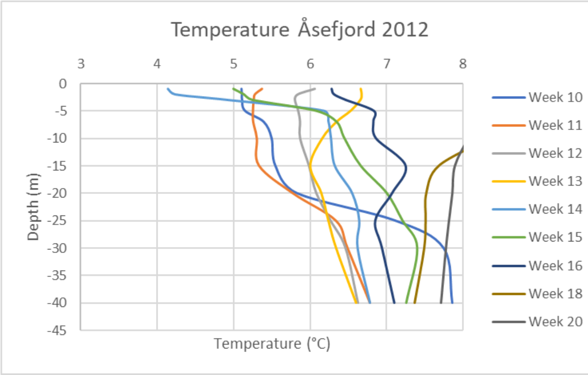
Week 20


Temperature Åsefjord 2012
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Depth (m)
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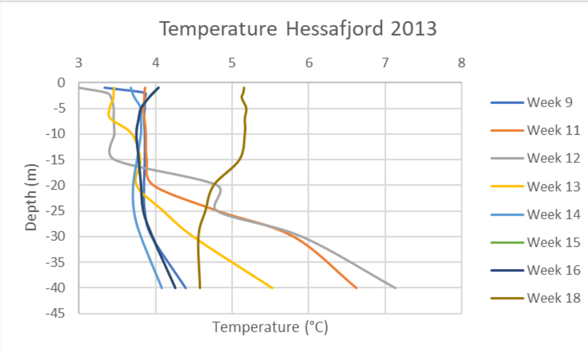
Temperature Hessafjord 2013
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Depth (m)
Temperature (°C)
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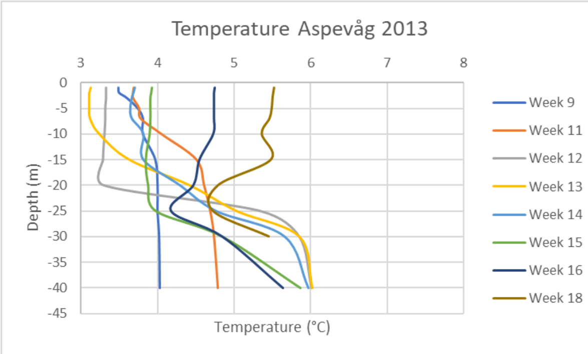
Temperature Aspevåg 2013
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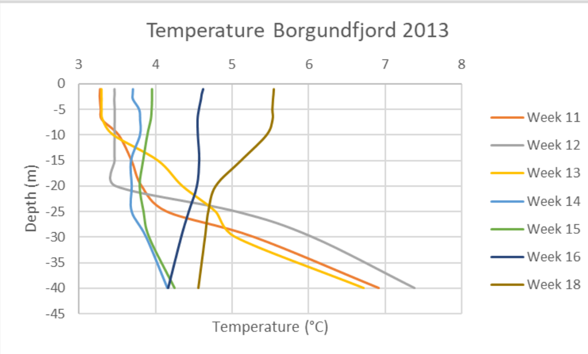
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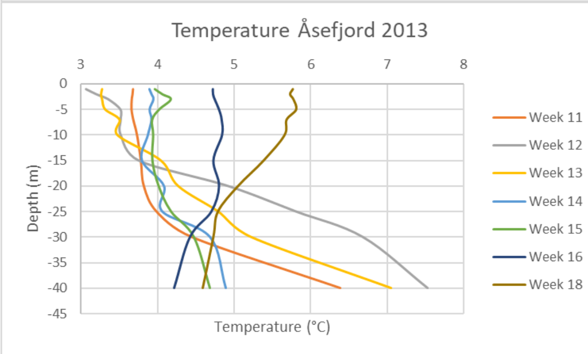
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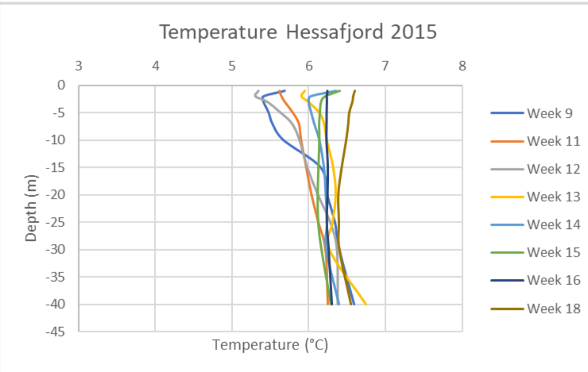
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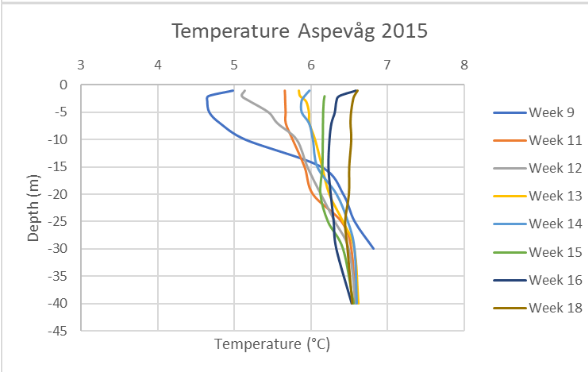
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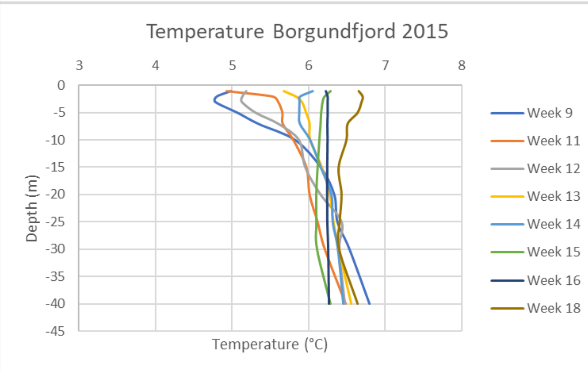
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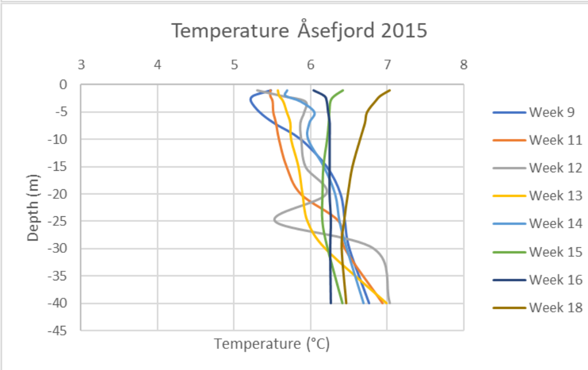
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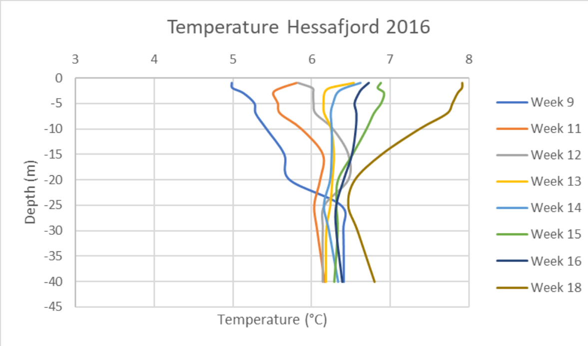
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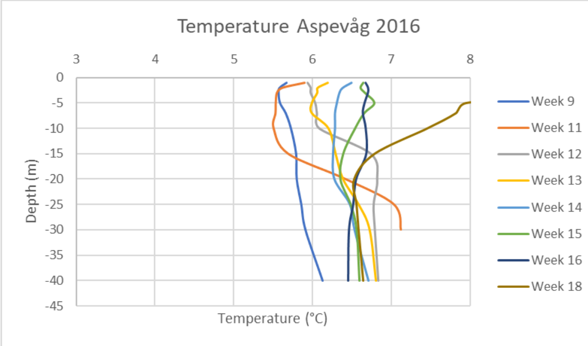
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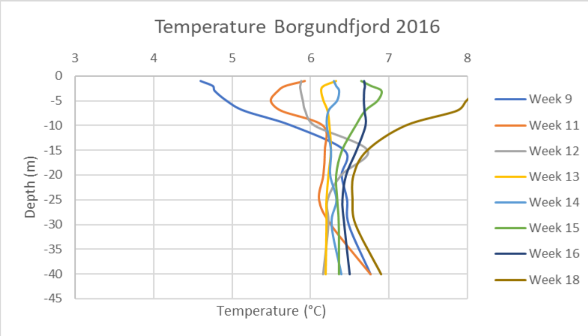
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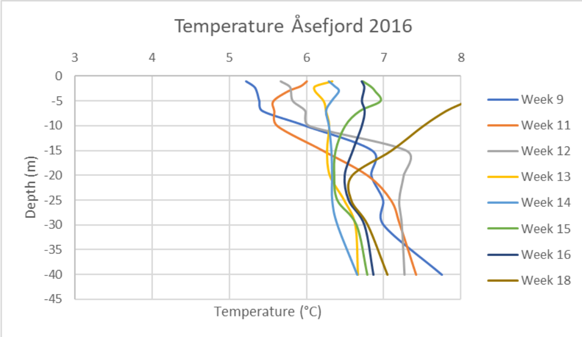
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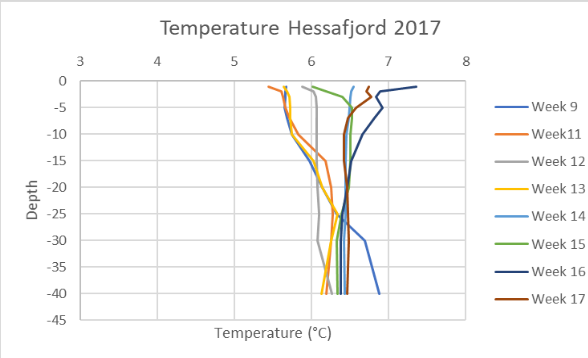
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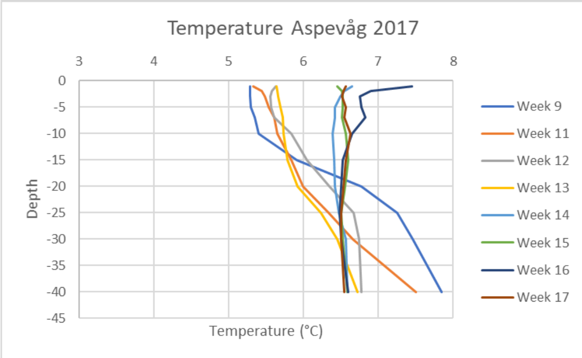
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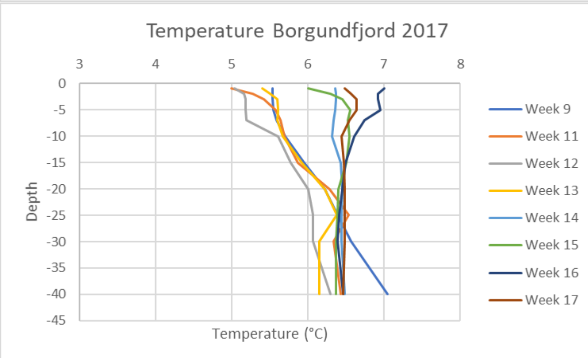
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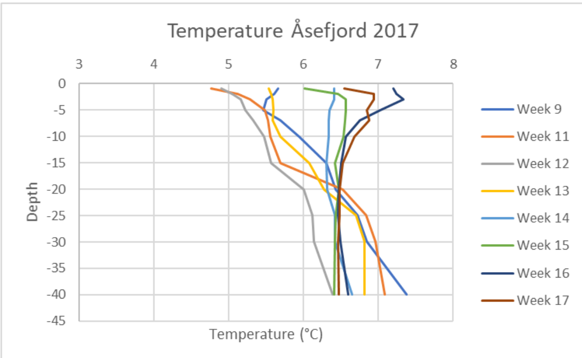
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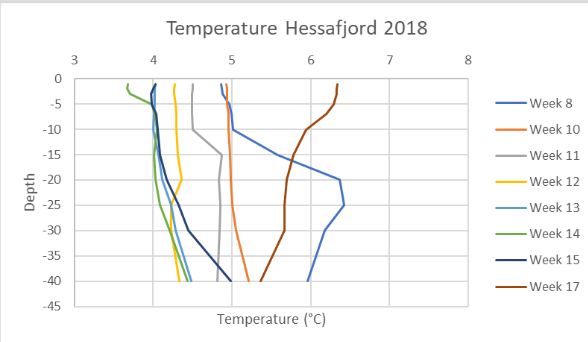
Temperature Hessafjord 2018
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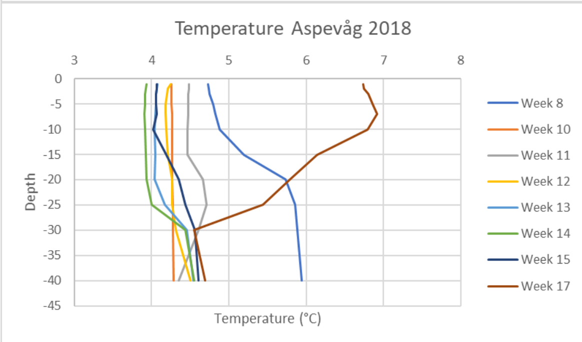
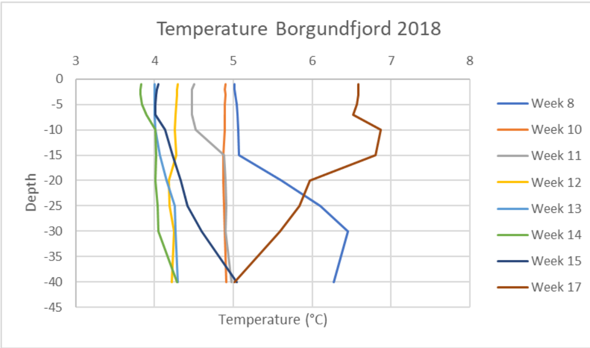
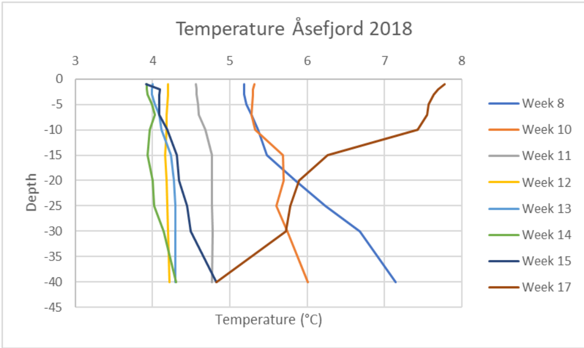
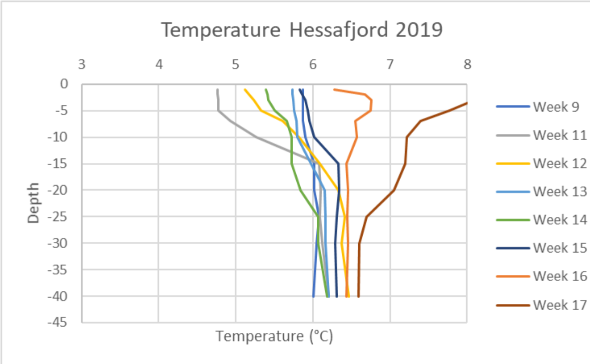
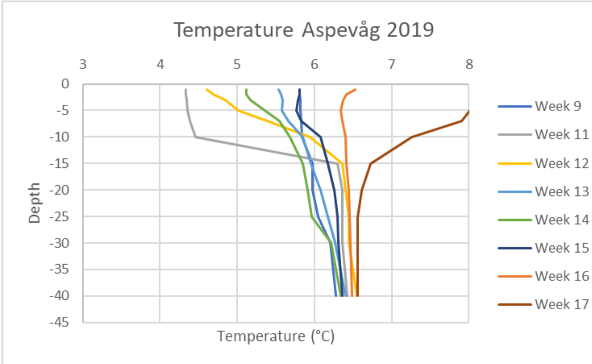
Week 15
Week 17

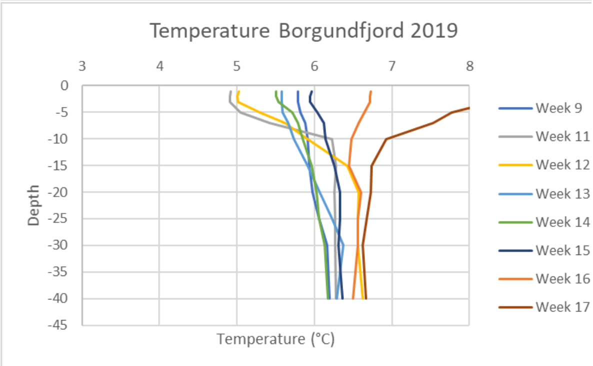

Temperature Aspevåg 2018
Depth
Temperature (°C)
Week 8
Week 10
Week 11
Week 12
Week 13
Week 14
Week 15
Week 17

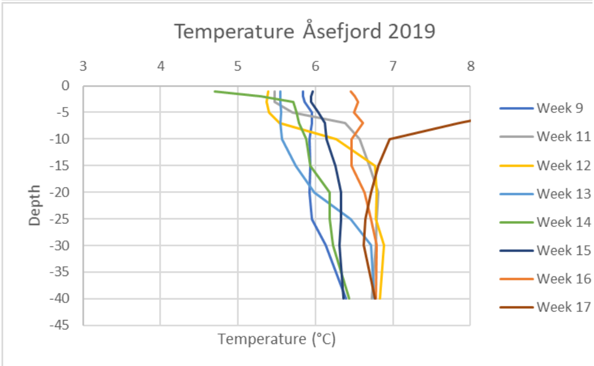




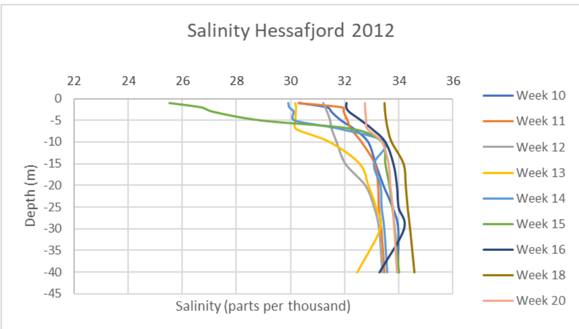


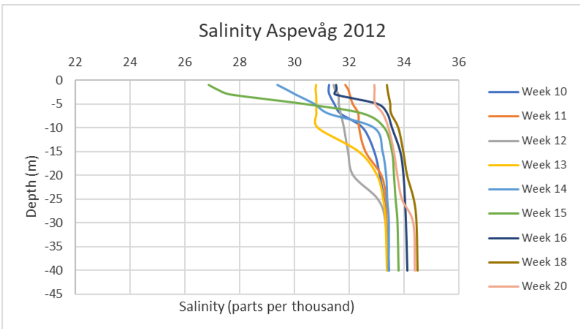


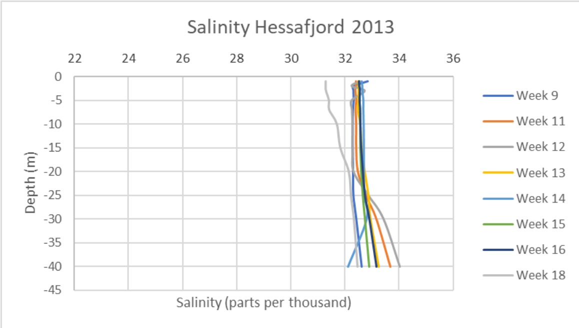


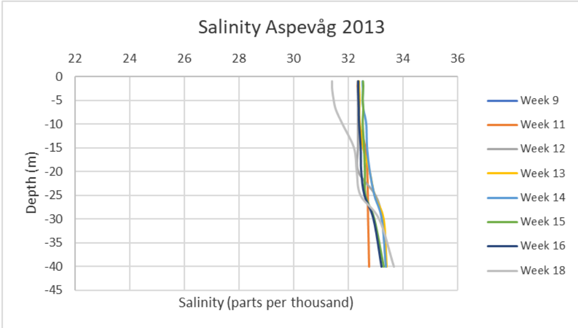


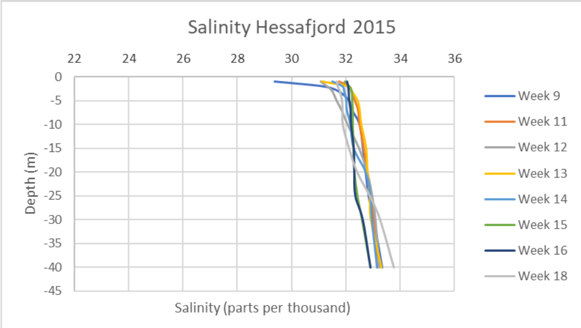
6.4 Appendix IV: *Salinity profiles for Hessafjord and Aspevåg 2012-2019 (excl. 2014)*

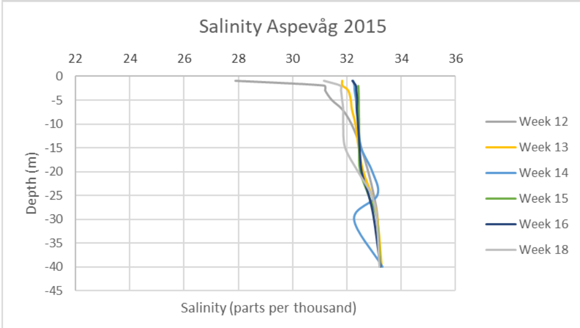


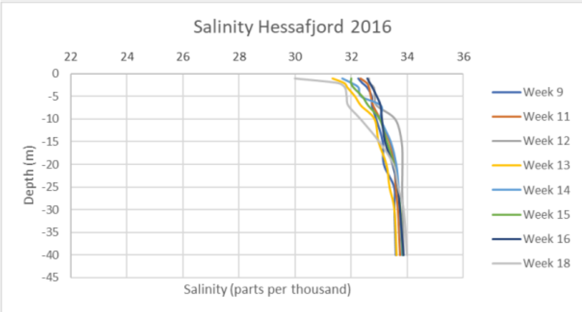


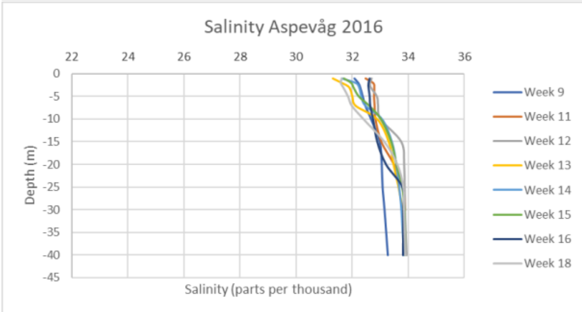

Salinity Hessafjord 2013
Depth (m)
Salinity (parts per thousand)
Week 9
Week 11
Week 12
Week 13
Week 14
Week 15
Week 16
Week 18

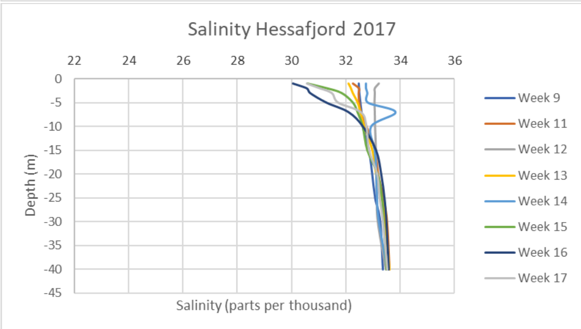

Salinity Aspevåg 2013
Depth (m)
Salinity (parts per thousand)
Week 9
Week 11
Week 12
Week 13
Week 14
Week 15
Week 16
Week 18

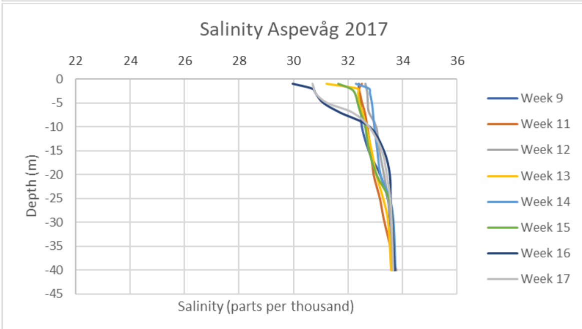

Salinity Hessafjord 2015
Depth (m)
Salinity (parts per thousand)
Week 9
Week 11
Week 12
Week 13
Week 14
Week 15
Week 16
Week 18

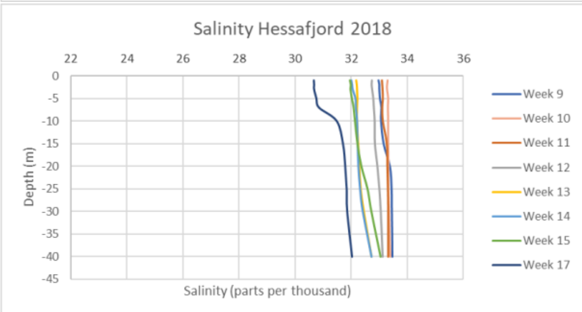

Salinity Aspevåg 2015
Depth (m)
Salinity (parts per thousand)
Week 12
Week 13
Week 14
Week 15
Week 16
Week 18

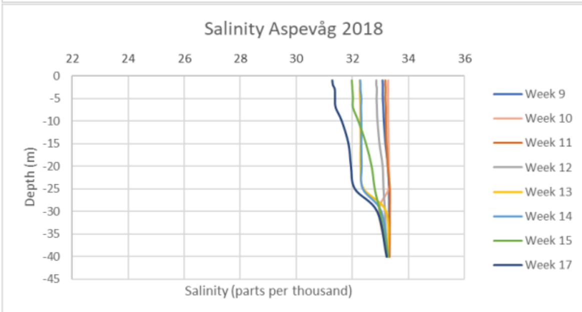

Salinity Hessafjord 2016
Depth (m)
Salinity (parts per thousand)
Week 9
Week 11
Week 12
Week 13
Week 14
Week 15
Week 16
Week 18

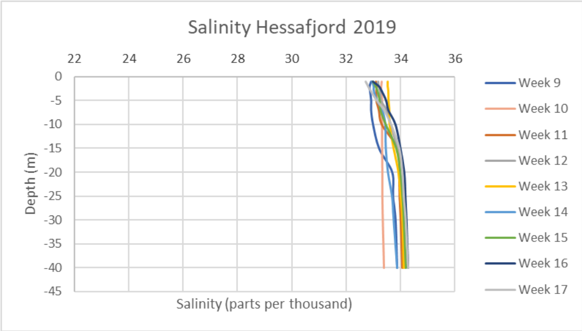

Salinity Aspevåg 2016
Depth (m)
Salinity (parts per thousand)
Week 9
Week 11
Week 12
Week 13
Week 14
Week 15
Week 16
Week 18

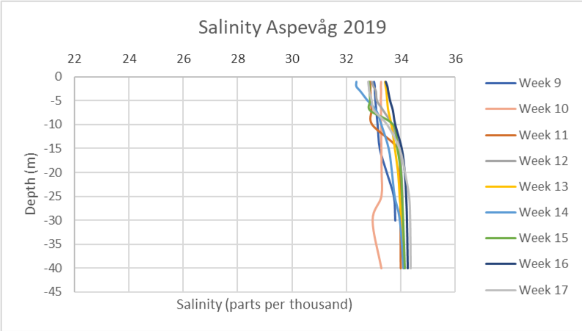

Salinity Hessafjord 2017
Depth (m)
Salinity (parts per thousand)
Week 9
Week 11
Week 12
Week 13
Week 14
Week 15
Week 16
Week 17


Salinity Aspevåg 2017
Depth (m)
Salinity (parts per thousand)
Week 9
Week 11
Week 12
Week 13
Week 14
Week 15
Week 16
Week 17


Salinity Hessafjord 2018
Depth (m)
Salinity (parts per thousand)
Week 9
Week 10
Week 11
Week 12
Week 13
Week 14
Week 15
Week 17

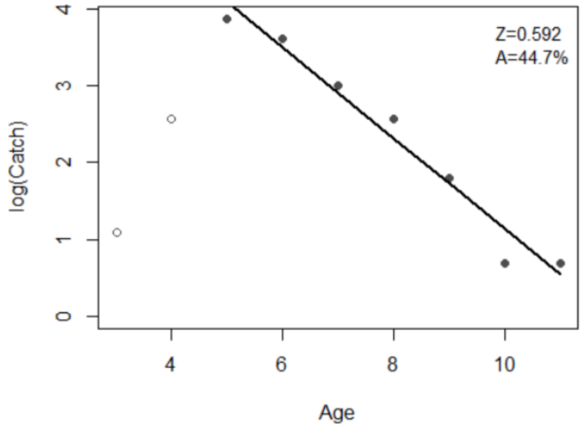

Salinity Aspevåg 2018
Depth (m)
Salinity (parts per thousand)
Week 9
Week 10
Week 11
Week 12
Week 13
Week 14
Week 15
Week 17

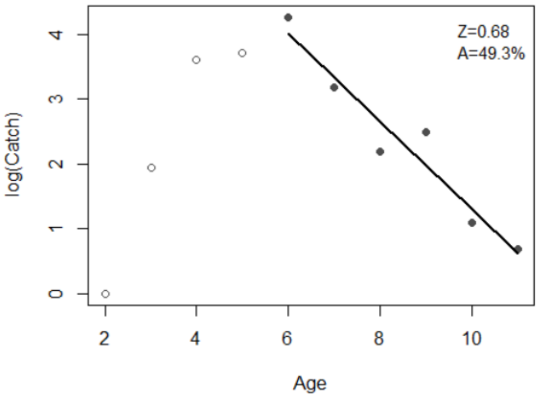

Salinity Hessafjord 2019
22 24 26 28 30 32 34 36
0 -5 -10 -15 -20 -25 -30 -35 -40 -45
Depth (m)
Salinity (parts per thousand)
Week 9
Week 10
Week 11
Week 12
Week 13
Week 14
Week 15
Week 16
Week 17


Salinity Aspevåg 2019
22 24 26 28 30 32 34 36
0 -5 -10 -15 -20 -25 -30 -35 -40 -45
Depth (m)
Salinity (parts per thousand)
Week 9
Week 10
Week 11
Week 12
Week 13
Week 14
Week 15
Week 16
Week 17

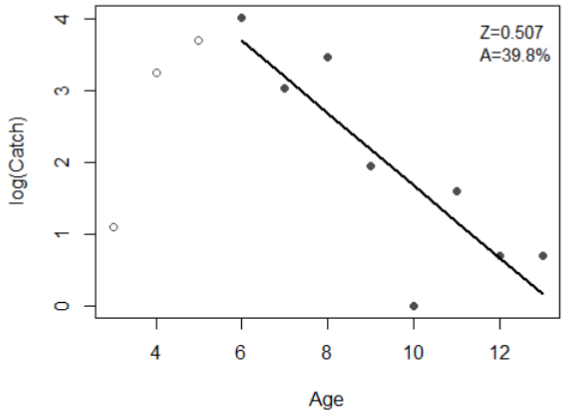
6.5 Appendix V: *Plots of catch-curve mortality estimates for Norwegian Coastal cod*

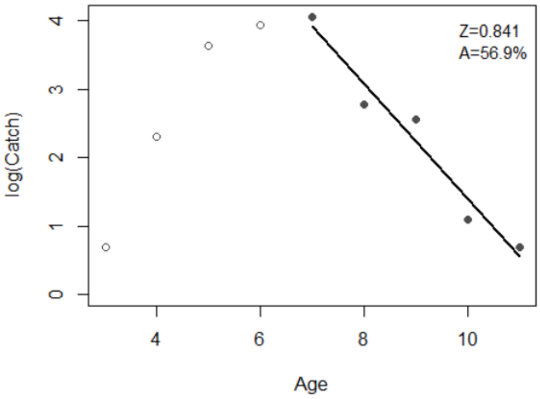
1996 2002



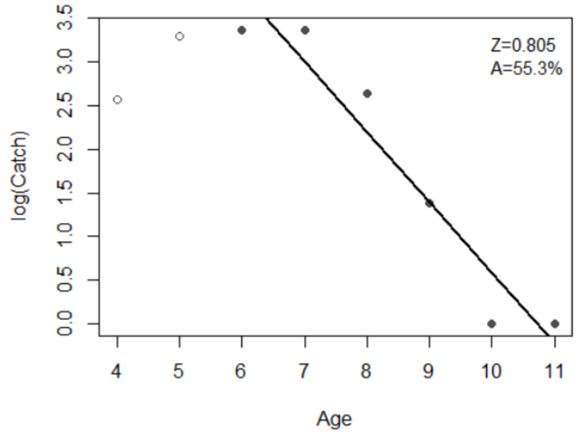


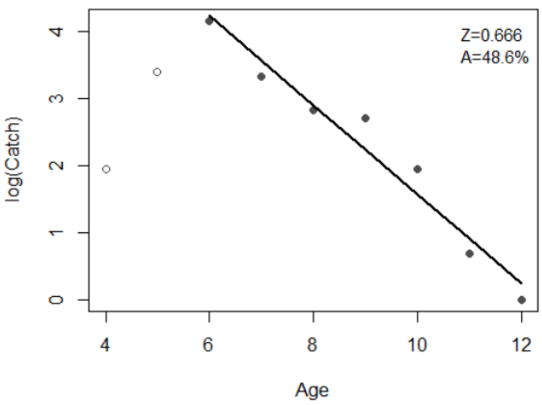
2009 2012



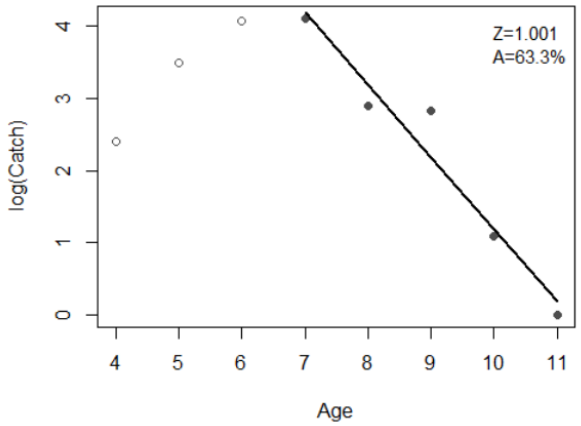


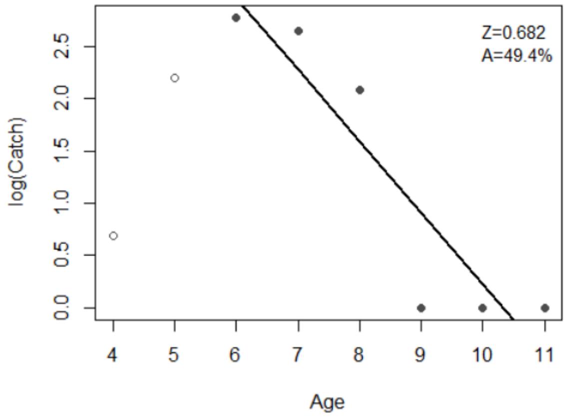
2013 2015



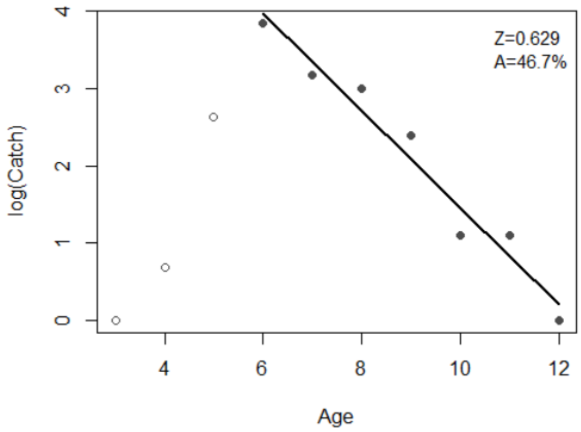


2016 2017

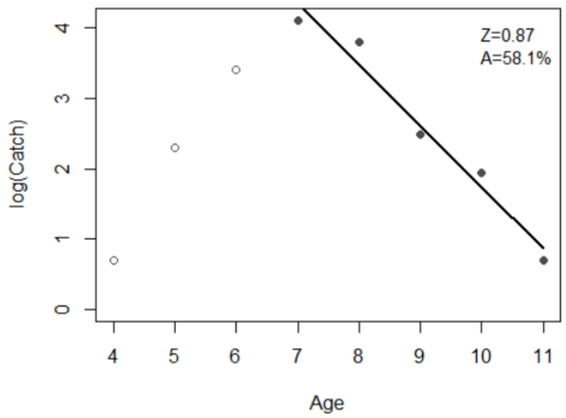




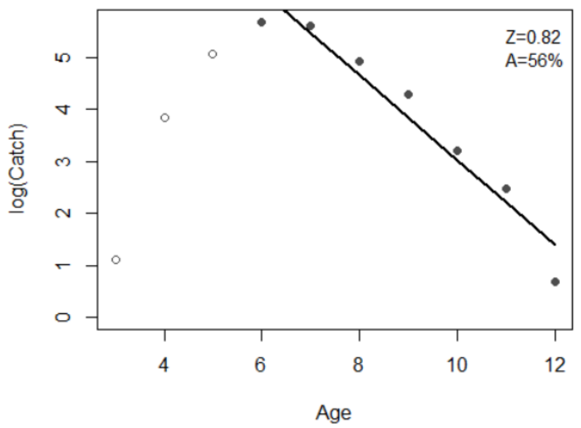
2018



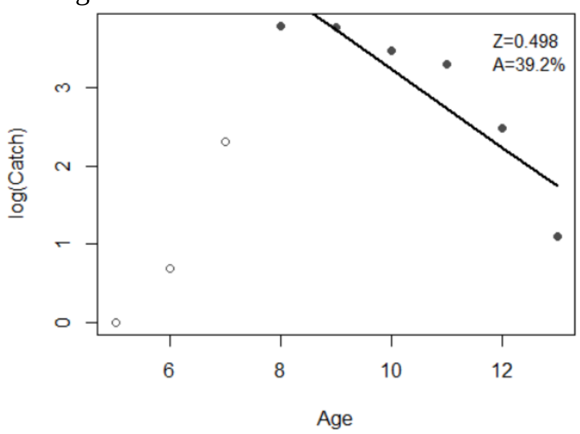
2019



Merged catches of NC cod from 2012-2019



Merged catches of NEA cod from 2012-2019



6.6 Appendix VI: *Regression coefficients for development of cod eggs.*

Table 6.1: Regression coefficients for development of cod eggs, used in equation 2.6. The numbers are derived from Thompson & Riley (1981).

	Regression coefficients	
Development stage	***A***	***B***
IA	-0.10	1.56
IB	-0.11	1.96
II	-0.11	2.26
III	-0.11	2.97
IV	-0.11	3.24

V	-0.10	3.46

6.7 Appendix VII: *Overview of the proportion of eggs retrieved in the area after 4 days of modelled drift*

Table 6.2: Overview of the proportion of eggs retrieved in the study area (Figure 1.1) after 4 days of modelled drift

Week	**Proportion retained**					
	2013	2015	2016	2017	2018	2019
8	-	-	-	-	0.81	-
9	0.13	0.77	0.78	0.94	-	0.97
10	-	-	-	-	0.46	-
11	0.87	0.74	0.85	0.82	0.85	0.73
12	0.92	0.80	0.61	0.92	0.59	0.87
13	0.85	0.82	0.55	0.70	1.00	0.95
14	0.73	0.73	0.86	0.74	0.73	0.89
15	0.99	0.89	0.81	0.93	0.94	0.81
16	0.91	0.94	0.84	0.83	-	0.93
17	-	-	-	-	0.90	0.76
18	0.68	0.43	0.62	0.85	-	-

6.8 Appendix VIII: *Fecundities*

a) Fecundity Norwegian coastal cod

The plot which the fecundity estimates of NC cod are based on, derived from Hannes Höffle (IMR, pers. comm.). Equation 2.11.1 equals the y in the top left corner of the graph.

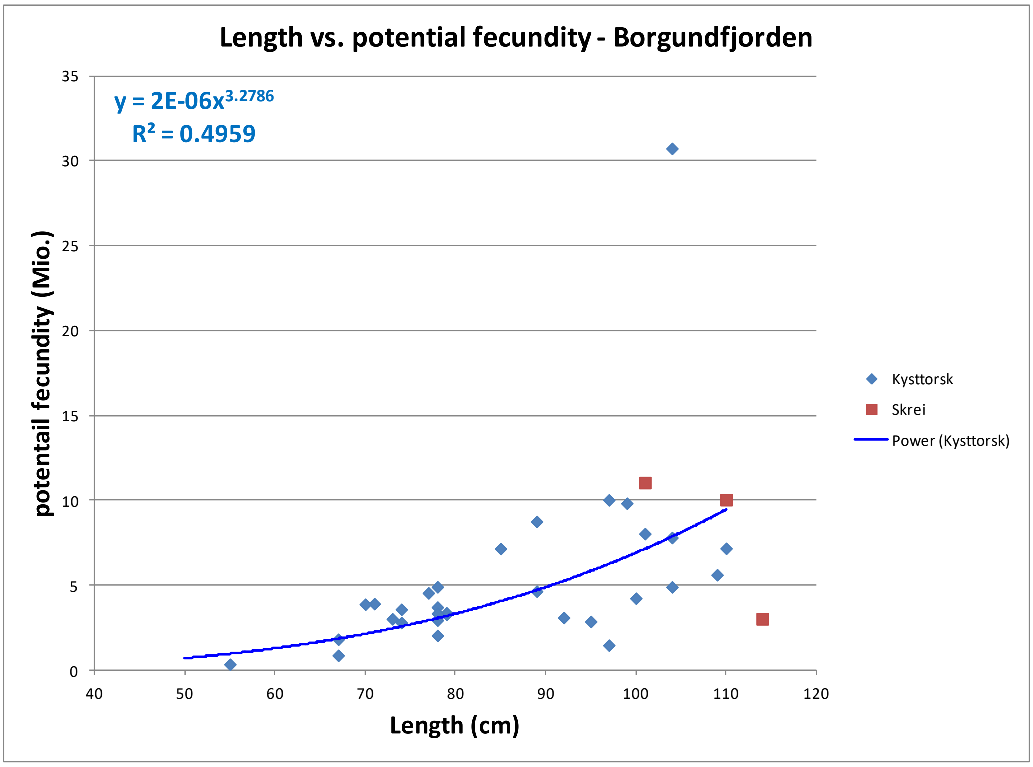


Figure 6.2: Potential fecundity of Norwegian Coastal cod. Equation 2.11.1 equals the y in the top left corner.

b) Fecundity Northeast Arctic cod

The plot which the fecundity estimates of NEA cod are based on, derived from Hannes Höffle (IMR, pers. comm.).

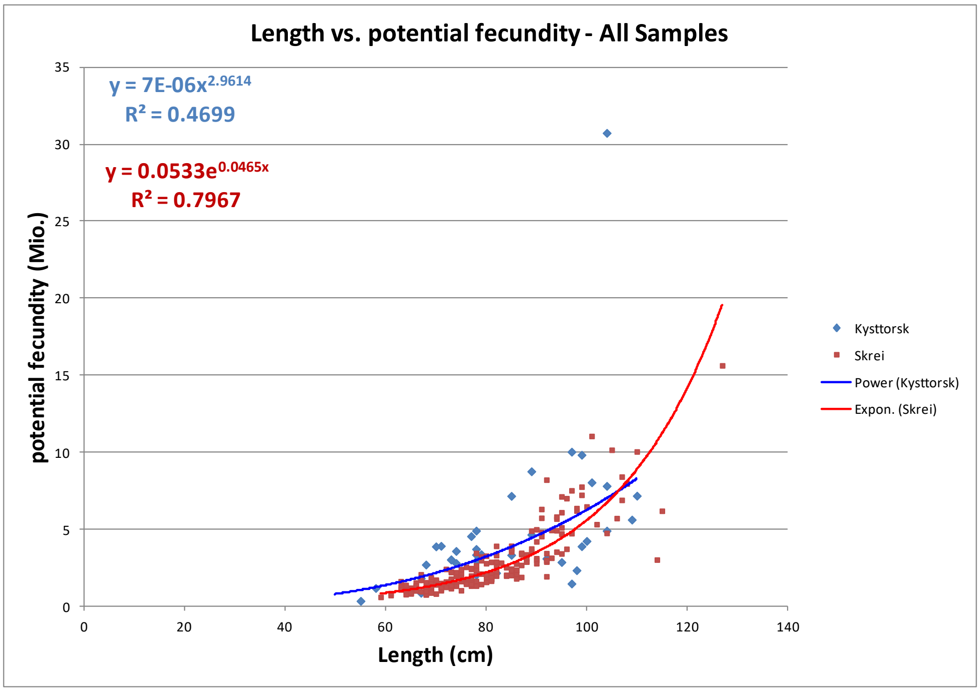


Figure 6.3: Potential fecundity of Northeast Arctic cod. Equation 2.11.2 equals the lower y (red) in the top left corner.