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Catch per unit effort and population structure of Atlantic cod, *Gadus morhua*, in the Inner Oslofjord during a catch ban period

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Natural Resource Management

Foreword

I would like to extend my greatest and most sincere thanks to my main supervisor, Jonathan E. Colman for your unending positivity and good mood, vast knowledge, and great advice, as well as having the most awesome boating skills I have ever seen.
I owe equally big thanks to professor Thrond O. Haugen for always welcoming me into your office, for your great support and guidance and for lending me your invaluable knowledge of statistics.

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Abstract

Atlantic cod populations in the inner Oslofjord have faced a serious decline due to overharvesting. Since 2019, a cod catch ban has been in effect, rendering all harvesting of the species in the Oslofjord illegal. This study aims to assess catch per unit effort, condition, and age distribution of cod in two areas in the fjord. One area is in the inner Oslofjord and have been sampled 1-3 times per year in 2019-2022. The other area is just north of the Drøbak sound and has seen sampled once per year in 2021-2022. In each zone, 20 fyke nets were placed randomly and stratified and checked every second day for a week. Tissue samples, scale samples, weight and length were taken for caught cod. Catch data was used to calculate catch per unit effort (CPUE) and was compared to studies published in both 2021 and 2013. Condition factor was calculated using weight and length measurements and scales were used to estimate age and back-calculate length-at-age.

CPUE in the inner fjord zones was around 0,2 cod per trap per day, with very little change over the years. CPUE in the Drøbak area in 2021 was extremely high (0,52±0,58) which was more than double the value form the inner fjord zones in 2012 (0,31±0,23). Condition factor in Drøbak averaged around 0,95, while in the inner zones it had dropped from around 0,9 in 2019 to around 0,7 in 2022, which is very poor. Age structure for inner fjord cod changed and included higher percentages of individuals 5-8 years old (32 %) in 2022 than before. No cod older than five years were caught in Drøbak, indicating this as the maximum age in that area. Back-calculated length for Drøbak cod was 2-5 cm shorter than individuals of the same age from the inner fjord zones. Instantaneous mortality dropped from Z=0,614 before the catch ban to Z=0,596 after the catch ban in the inner fjord zones. In Drøbak it was at Z=0,576.

The results do not indicate recovery of the cod population in the inner Oslofjord after the catch ban but showed higher CPUE levels in Drøbak. Drøbak cod also had higher condition factor, but were shorter and died earlier, perhaps because of fishing. Poor condition factor may have reduced recruitment in the inner fjord cod, but the catch ban is helping as we see an increased abundance of older than 5-year-old cod, as should be expected in a population not subjected to harvest.

Introduction

What is the seafaring nation of Norway without her oceans and marine resources? Among the marine resources available to Norway, the marine biota is of the utmost importance. Healthy and intact marine ecosystems provide many ecosystem services ranging from provision of aquaculture and fisheries, to regulations of temperature (Goulletquer et al., 2014).

In the southeast of Norway, by the capital and largest city, Oslo, lies the Oslofjord. For well over a millennium, humans have settled and used the Oslofjord and the surrounding coastal areas. This fjord has historically been immensely rich and diverse. Practically every fish species found along the Norwegian coast could be found here at some point and the people living along the fjord have always taken advantage of this abundance (Kleiven et al., 2016). Despite huge fishing efforts in historic times, the primitive and simple fishing equipment did not dimmish the stocks significantly. However, the introduction of new technology in fishing gear, like trawlers that were introduced to Norway in the year 1908 (Hallenstvedt, 2020), but became mainstream around the 1950s opened a new era of commercial fisheries in the fjord (Moland et al., 2021). For decades afterwards, the intensity of the fishing increased, leading to overfishing of several stocks. Of the fish species in the fjord that were most affected by this overfishing is perhaps the Atlantic Cod, *Gadus morhua*, the most important.

Atlantic cod, hereby known as cod, has been the most important marine fish species, both culturally and economically through Norwegian history. Dried cod have been one of Norway’s most prominent export wares for centuries. It was sold and consumed as far as to Caribbean islands like Jamaica, as well as several Mediterranean countries like Spain (Kurlansky, 1997).

Cod have, in fact, had similar socioeconomic importance in most countries with coastlines that border to the North Atlantic. Canada, Iceland, and the UK to name a few also have a history of economics that have relied on cod fisheries. Cod fisheries in Iceland and the UK played a vital role in the establishment of 200 nautical mile exclusive economic zones (EEZ) through what is popularly known as the Cod Wars (Kurlansky, 1997).

Because of cod’s socioeconomic importance, overharvesting has caused cod stock sizes to dwindled worldwide over the last couple of decades. This was undoubtedly most prominent in the Newfoundland cod stock in Canada in the early 1990s where the cod population collapsed to about 1% of its historic size and range (Bavington, 2011; COSEWIC, 2010; Hutchings & Rangeley, 2011). Comparatively, the cod population sizes in the Oslofjord has plummeted since the year 2000, but more severely from 2016 to 2019 (Knutsen et al., 2022). This population was much smaller than the Newfoundland one, and the population decline less steep, yet the situations are comparable. In Norway, cod is categorized as “Viable” (Hesthagen et al., 2021) despite descriptions of reductions in three out of four of the country’s main stocks. The species’ IUCN Red List status is “Vulnerable” (Sobel, 1996), although this assessment is 28 years old, and thus, arguably, in need of an update.

There are several hypotheses as to why the cod declined so dramatically in the Oslofjord. Although there is little doubt that commercial overfishing was the most detrimental driving factor behind the disappearance of the Oslofjord cod stock, factors like recreational fishing, climate change, seawater pollution and spawning site and habitat destruction all played their respective roles (Dolven et al., 2013). Time and again research has shown that the effect recreational anglers can have on the population size of vulnerable fish populations may be vastly more detrimental than initially believed (Abbott et al., 2022; Cooke & Cowx, 2004; Haase et al., 2022; Kleiven et al., 2016; Schroeder & Love, 2002).

As a response to this decline, several attempts to strengthen the cod populations in the fjord and surrounding areas has been implemented. In 2017 a program called “Krafttak for kysttorsken” which translates to “Power move for the coastal cod” was initiated. It ended in 2021 and was a collaboration between marine researchers and conservation institutions and aimed at mapping out the situation for coastal cod (among other species) in the outer Oslofjord and the Skagerrak coast. It concluded that, while the Oslofjord has several challenges like terrible water quality as a result of poor water treatment plants and agricultural runoff, effects of heavy bottom trawling on benthic habitats and fishing pleasure, there is still grounds for recovery for the cod population (Moland et al., 2021).

The 15th of June 2019 the Directorate of Fisheries passed a regulation stating that all fishing of cod, both recreationally and commercially, was prohibited in the whole Oslofjord year around. The regulations were updated in November of 2022 allowing the Directorate to grant one dispensation to fish for cod with gill nets in the inner Oslofjord to boats that conducted this activity prior to the ban. This was done to allow for the sale of local, fresh fish on the piers, supported by cultural and traditional arguments ("Forskrift om forbud mot fiske i gytefelt for torsk," 2019). The ban on cod catches ranges from Ellingsvik to the south of Kragerø, following the coastal baseline all the way to the Swedish border (figure 1). If anglers happen to catch some cod within this zone, they are obliged to gently untangle them from the equipment and release them into the wild.

The regulation included another ban as well, stating that all fishing of any species is prohibited within 14 defined cod spawning areas in the time-period between January 1st and April 30th. These 14 spawning areas are spread out from Lindesnes, along the Skagerrak coast and out to the Swedish border (figure 1).

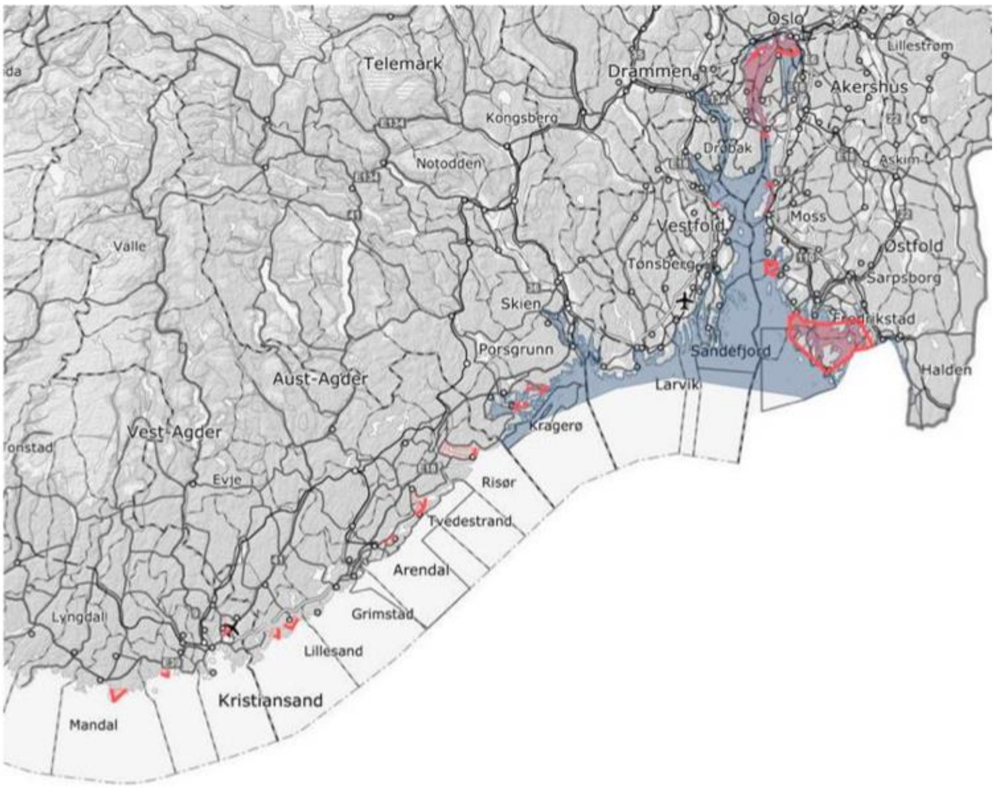


Figure 1. The total range of the cod fishing ban in the Oslofjord and the Skagerrak coast. The gray shaded area is where the fishing of cod is prohibited the whole year. The fourteen red shaded areas are defined cod spawning grounds where all fishing is prohibited in the time period between January 1st and April 30th.
Map taken from Fiskeridirektoratet
https://www.fiskeridir.no/Fritidsfiske/Artar/Vern-av-kysttorsk-i-soer.

Recently, a master student at the Norwegian University of Life Sciences conducted research on the population size of cod in the inner Oslofjord following this catch ban (Craig, 2021). He started trapping and tagging cod only a few months after the ban was launched and continued for two years. As it takes time for protected populations to replenish themselves toward their historic numbers, it was no surprise that his result did not indicate any recovery of the cod populations (Knutsen et al., 2022). Quite on the contrary, Craig (2021) found that due to high levels of water pollution, habitat change and nutrient deficiencies, cod in the inner Oslofjord had considerably poorer condition factor (as a proxy for health) than cod populations elsewhere (Craig, 2021).

The Oslofjord is usually divided into two main basins, The inner and outer Oslofjord are separated by a fjord sill in the narrow Drøbak sound which is about 1000 meters wide and 20 meters deep (Askeheim, 2021). This sill prohibits free water circulation into the inner Oslofjord, making this area more vulnerable for pollution and poor water quality. The surrounding lands to the Oslofjord are subject to high intensity agriculture, leading to fertilizer runoff causing nutrient pollution and reduced visibility in the water column. High population density and large urban areas along the fjord also causes urban runoff, and certain levels of pollution from water treatment plants. Added to the naturally anoxic benthic conditions in many regions of the inner Oslofjord like the Bærum basin, and the stressor following global warming, the inner Oslofjord presents challenging conditions for a cod population to recover, even after removing the fishing pressure.

On several occasions however, depleted cod populations have managed to recover under suitable condition and good management (Lindegren et al., 2010). This is perhaps most prominent in Icelandic waters where good management through quotas on cod fisheries, have facilitated the recovery of the local cod stocks since the 1970s (Gunnlaugsson & Valtysson, 2022). Although not as significantly, cod stocks off the Greenland coast has also recovered to some extent after their respective collapse in the 1970s (Werner et al., 2020). Research from other regions however, states that management measures for cod populations have not resulted in an increased number of cod or had inconclusive results on the matter (Bryhn et al., 2022).

It can then be said that there is no guarantee that the cod population in the inner Oslofjord will recover after the initiation of the catch ban. Following the methodology from previous research (Craig, 2021; Ski, 2013), this study will attempt to assess the continuation of the fyke net-based catch per unit effort (CPUE) of cod in the inner Oslofjord in order to compared with previous years both before and after the catch ban. I will assess the population density and population structure developments in two areas in the fjord. The inner fjord area, which is believed to be highly impacted by organic carbon loads, and the mid fjord by the fjord sill (Drøbak area) where organic carbon loads are believed to have less of an effect.

Better water circulation by the sill results in better water quality around the entrance to the inner fjord. Theoretically this could mean more and healthier cod, as well as the proximity to more open water systems heighten the probability of interactions between outer fjord/ Skagerrak cod and inner Oslofjord cod. In addition to comparing catch per unit effort between the two sampling areas and previous findings, this study will assess and compare condition factor of the individuals.

Study goals and hypothesis

The goal of this study is to assess whether the cod population in the Oslofjord, both in the inner fjord area and by the Drøbak sound, is increasing in abundance, size, age, and condition.

I hypothesize that the catch per unit effort of cod will have marginally increased since the implementation of the fishing ban in 2019. I also hypothesize that the CPUE of cod near Drøbak and closer to the fjord sill is going to be larger than in the inner fjord zones. I believe the same to be true for the condition of the cod.

Lastly, I expect to see more specimen at both ends of the age spectrum. Older specimen should be more abundant in the absence of fishing mortality. More older and mature fish should also lead to more juveniles.

Methods

The methodology in this thesis is in large the same as the method described in a recent master thesis (Craig, 2021). Sampling for this thesis has been done in the same zones and the dataset is in large a continuation of this previous dataset. This with the exception of two new sampling zones (Drøbak area), that were not present in the previous study. Similar to this study, Craig (2021) intended to estimate the population size of the fjord cod in the inner Oslofjord using the Huggins robust design mark- recapture model (Huggins, 1989). However, neither the sampling in 2019 and 2020 nor the sampling in 2021 and 2022 yielded enough re-captures to use this technique. This resulted in Catch per Unit Effort (CPUE) becoming the utilized method for estimating relative population size of cod in this study.

Study species

Atlantic cod is a gadiform fish species native to the North Atlantic Ocean. It ranges from the east coast of Canada in the west to Greenland, Iceland, the Barents Sea, Skagerrak and east to the Baltic Sea. The Oslofjord cod population is a sub-group of the larger Skagerrak stock, which again is a sub-group of the "Coastal cod below 62^0N" stock, one of the four main Norwegian cod stocks (Hesthagen et al., 2021).

Although occasionally found down to depths of 600 meters, they are rarely seen outside of the continental shelf. Cod are benthic opportunistic predators with a diet consisting of smaller fish, fish eggs, crustaceans and mollusks to name some (Kurlansky, 1997). Individuals have been observed to reach the age of 25, yet the average maximum age for Norwegian cod is about 7 years old (Hesthagen et al., 2021). Adult bodies may reach up to 1.6 meter given the right conditions. Cod becomes sexually mature between the ages of two to four, although this varies between populations and can take longer in the colder regions of the North Atlantic (Brander, 1994). Generally, the spawning season occurs between January and April, however, this also varies between populations and their locations as it is temperature dependent (Brander, 1994; McQueen & Marshall, 2017).

During spawning season, the cod congregate in shallow spawning grounds, usually very close to the shore. Cod seem to prefer spawning grounds with complex substrate composition with a mixture of sand, rocks and boulders (González-Irusta & Wright, 2016; Grabowski et al., 2012). Here they undergo a vocal mating ritual and spawn their eggs (COSEWIC, 2010; Grabowski et al., 2012; Kurlansky, 1997). A fully grown female can lay up to nine million eggs each spawning season. It is however, only expected that about one in a million eggs survive to maturity (Craig, 2021; Kurlansky, 1997). Hatching of the eggs can take between 10 and 40 days, depending on temperature and population.

Upon hatching, the cod larvae have a yolk sac to help them sustain themselves. When this yolk sac is fully consumed after 2-3 days, the larvae's jaws open and they begin exogenous feeding on plankton as they themselves float planktonically in the water column. The larvae stage generally lasts somewhere between one to two months, in which the cod can increase their body size up to forty times. When the cod exit the larvae stage, usually in May – July, they undergo metamorphosis and become juvenile cod at between 4 cm and 7 cm (Ellertsen et al., 1980; Oomen et al., 2022). Throughout their first summer and fall season, juvenile cod averagely reach sizes of 14 – 20 cm (Craig, 2021; Aalvik et al., 2015; Aalvik, 2013).

Study area

Although the catch ban on cod encompasses the Oslofjord in its entirety, (inner, outer, and various side-fjords) the range of this study is limited to the inner fjord, sometimes known as Vestfjorden. This is also one of the 14 spawning sites where all fishing is prohibited in the spawning season from January to April.

Cod traps were placed in five different zones across the inner Oslofjord, between the Drøbak sound and Oslo city. Three zones were located in relative proximity to each other in Vestfjorden and the Bærum basin towards the northern end of the fjord (figure 1) These zones were intended to form a sort of environmental gradient from (3) secluded coastal basin, to the transition between said basin and more open water habitats (1), to habitats that are affected by open water and better circulation and currents (2).

These zones are identical, and thus directly comparable to a previous master study conducted by Craig (2021) and Ski (2013). Here sampling has occurred up to three rounds a year for the last four years.

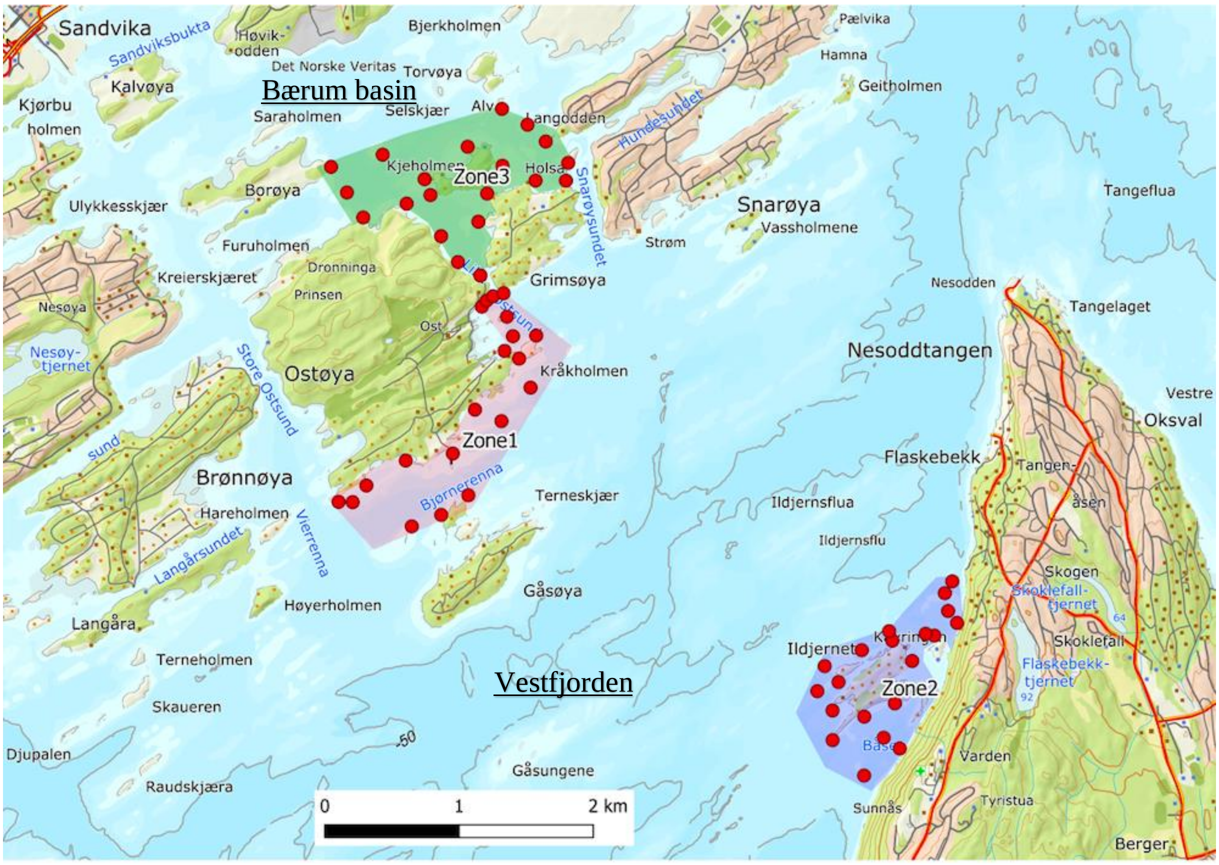


Figure 2. Location of the three cod trapping zones in the Bærum basin and Vestfjorden in the inner Oslofjord (shaded polygons), and the exact 20 locations where traps were placed every round from 2019 to 2022 (red circles).

Additionally, the last two years, sampling has been done in the September in two zones further south in the fjord. Just north of the Drøbak sound, and thus, just inside the inner fjord, lies the island Håøya. The last two zones are located around the northern tip (North) and off the southern tip (South) of this island (figure 3). The idea behind sampling from these two zones in addition to the three established zones further inside the fjors is that the water quality is believed to be better here. Especially in regard to pollution from cities and sewage treatment plants. It is additionally hypothesized that the cod population this close to the fjord sill are more likely to migrate out of the fjord and interact with cod that migrate into the fjord.

The three zones in Vestfjorden and the Bærum basin (zone 1, 2 & 3) will later be referred to as “inner fjord,” whilst the two zones around Håøya outside the city of Drøbak will later be referred to as “Drøbak.”

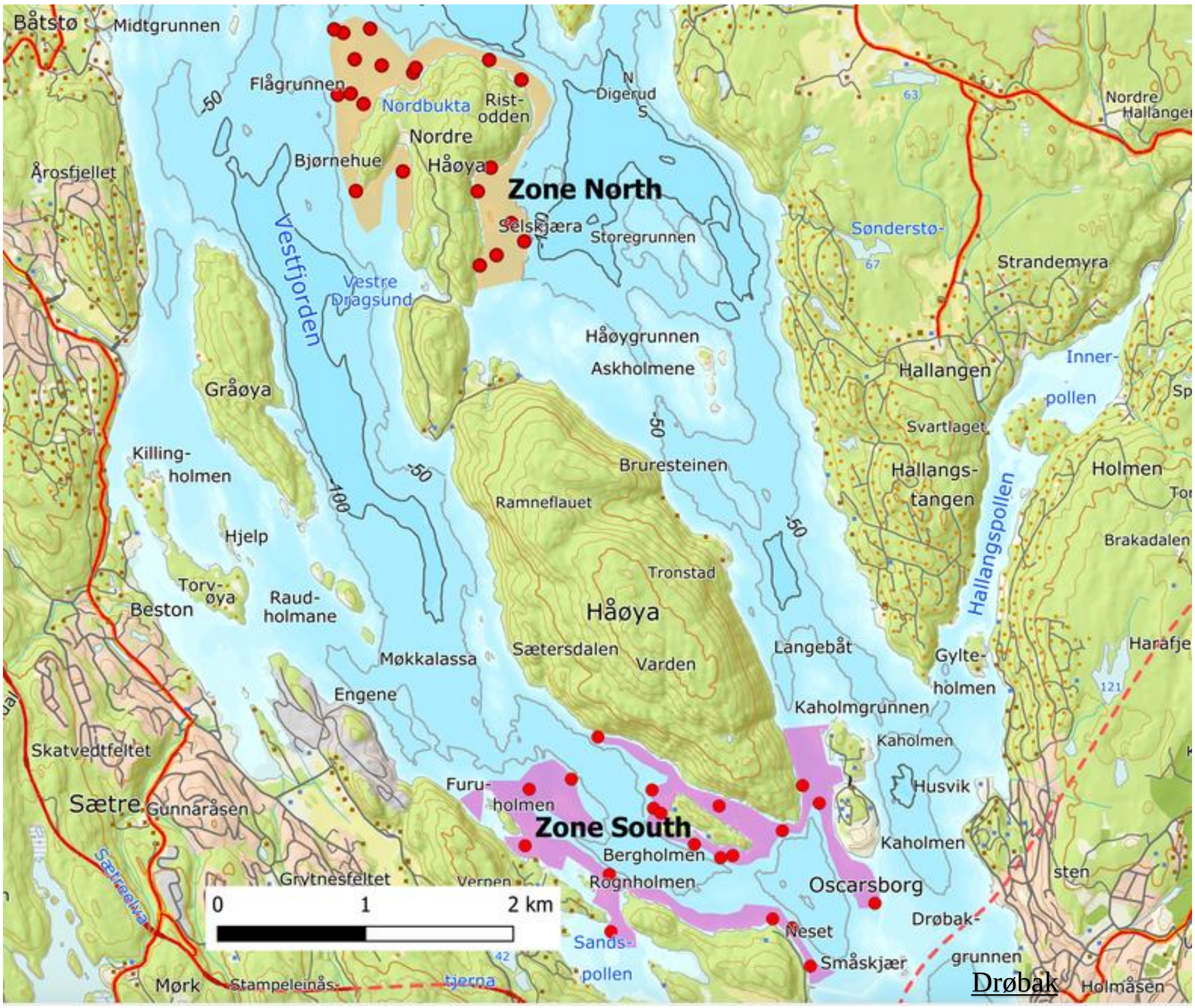


Figure 3. Location of the two cod trapping zones outside the city of Drøbak (shaded polygons) and the exact placement of the 20 traps from 2021 to 2022 (red circles).

Trapping

In each zone, 20 cod traps were set. The exact locations were randomly chosen with the software QGIS. In addition to a randomized spatial distribution, the locations were stratified, meaning that in each zone half of the traps were set at relatively shallow depths, while the other half are set at deeper depts, yet no deeper than 30 meters. The exact location for each trap was logged so that the same location could be used across sampling rounds and years, allowing for better comparability. Yet the 360° orientation of the trap varied between sets to limit biases towards cod movement patterns.

Once set, the traps were checked every second day, which means that the caught individuals may have been trapped at any point the last 48 hours. After a week of sampling in one zone, the cod traps were moved to the next zone. Hence, this resulted in three sampling occasions in each zone per round. Sampling in the three zones in inner fjord, was conducted three times a year. One in the early spring, just after the ice out. Second, in the fall (September and October) and lastly in December just before the bays in the fjord froze. Being benthic fish, cod prefer colder water, and the survival rate of cod caught and handled when the surface water temperature is above 16ºC is considerably lower (Craig, 2021). In the two Drøbak zones, I only had one sampling round per year. This occurred in late September.

The type of cod traps used in all five zones across four years of sampling were fyke nets. A fyke net is a trap placed along the seabed and has the potential to catch most benthic fauna (figure 4). Animal groups frequently caught in the fyke nets were crustaceans like lobster and crabs, gadiform fish species like cod and pollock, as well as several species of wrasse and flounders. Fyke nets are constructed by three main parts. At either side are two series of consecutive trap chambers that work in much the same way as eel and lobster traps. The last of these chambers at each end is called the codend and has an opening that can be opened, closed, and locked with a string and some knots. It is through the opening in the codend that most caught specimen are relieved of the trap. Connecting the two sections of chambers is a leaded leader net whose purpose, contrary to the likes of gill nets, is to lead any passing fish towards and into the trapping chambers at either end of the net. The fyke net as a whole is held down by two weights at either end, one of which is further connected to a rope with a buoy at the end. For legal reasons, each buoy is marked with "scientific sampling (prøvefiske)", NMBU, and the phone number of Professor Thrond Haugen. Additionally, each buoy is marked with a number that is unique for that fyke net. This allows for the assessment of the catch rate of individual fyke nets in case some show consistently lower catch yields.

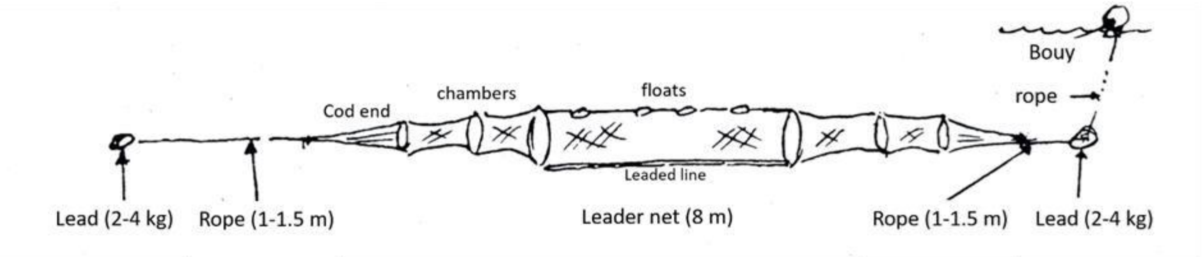


Figure 4. Schematic drawing of a fyke net trap with a leaded leader net, trap chambers and cod ends, all attached to weights, rope, and a buoy.

Tagging and sampling

Once on board the boat, the openings in the codends are opened and the catch is emptied into a large tray filled with seawater. Then the represented species were quickly determined and the number of specimens of each species counted. This is noted before the individuals are gently released into the water again. In the case of cod in the fyke nets, the sampling was a little more extensive. Each cod was gently taken out of the tray of seawater and placed on a wet towel (figure 5). Part of this towel was then placed over the cod's head to prevent panic and excessive movement from the fish. All sampling was done without anesthetics to keep handling time to a minimum. The length of the fish was then measured using a measuring tape, and for the most part rounded up to the closest whole centimeter. After this, all individuals measuring less than 30 cm were released into the wild again. These young and small individuals are still in a more vulnerable life stage and are less resilient to external stress damages. Additionally, the added stressor of the external floy-T tag has been shown to heighten mortality in young cod (Sandford et al., 2020; Svåsand, 1998). For these reasons, only individuals measuring above 30 cm were further handled and tagged.

With a small knife or twicers, scales from the fish's side were scraped off as gently as possible, and then placed in an envelope. The scales were later going to be used for estimating the age of the individual and back-calculating length at age.

Tissue samples were collected by cutting a tiny piece of either the caudal or anal fin with a scissor and placed in alcohol in a screwcap cryo vial. The vial was also stored in the same envelope as the scales. The tissue samples are going to allow us to sequence the individual's DNA in future genetics analyses.

Figure 5. Photograph from in situ sampling. The cod is placed on a wet towel that is then placed over its head. Then it is measured, tagged, sampled from and the weighed. Photo: Ane Mæstad.

Tagging the fish was done using a floy-T tag with a serial number (one letter and four numbers) and an NMBU email address (figure 6). The purpose of the serial number was to conduct the mark- recapture model and assess any potential migration in and between zones. The email address was there to allow any fishermen that were not part of this project to report any finds if they caught the cod on their own. No such emails have been received by the university since the start of the project in 2019. The floy tag was fastened in the muscle tissue of the fish just below the dorsal fin and using the spines in the dorsal fin to anchor it in place.

Tags were put in place using a tagging pistol (Mark III regular pistol) with a heavy-duty needle (figure 6).

Figure 6. Photograph of the tagging equipment used. Mark III regular tagging pistol with a heavy-duty needle (left) and external Floy tags with a university email address on (right). Photos: Jonathan Colman.

Lastly, the cod was removed from the wet towel and put into in a wet nylon shopping bag and weighted with a fish weight. The weight was recorded in grams and together with the length measurements were used to calculate the condition factor of that individual. In December 2022 an attempt was made at weighing the small cod below 30 cm in length. This weighing encountered several measuring complications and the data ended up being discarded from this study.

Condition factor

Condition factor (k), a number indicating the length adjusted weight of an individual fish, was calculated using measurements of length (cm) and weight (g). This was done following the approaches of Fulton's *k*-factor (Froese, 2006; Ricker, 1992), and utilized the formula: $k=\frac{W}{L^3} \times 100$.

Scale analysis

Estimating the age and growth rate of fish can be done by analyzing several different calcified or bony structures like otoliths, vertebrae, fin rays or scales. In this study, scales were used since the sampling of scales from live cod does not necessitate any noteworthy damage to the fish.

Cod scales have been used to estimate the age of Norwegian cod for around 90 years and is a verified method (Dannevig, 1933; Aalvik et al., 2015). As fish grow with age, so does their scales. The scales, however, grow in small increments, and leave behind small dark lines that circle the central plate. These lines are called sclerites. Since cod, like most other coastal fish species, are ectothermic, their metabolic and growth rate is dependent on the ambient seawater temperature (Fry, 1947; Oomen, 2019). This means they grow faster in summer when the water is warmer than in the cold winter months, resulting in larger gaps between the sclerites in the scales in the summer than in the winter. The narrow gap between the sclerites from the slow growth during winter months will, if viewed from a little distance, create significantly darker circles in the scales. These are called annuli and not entirely unlike the growth rings in a tree trunk can be counted to indicate the number of winters the individual fish have lived through. Knowing that cod usually hatch and undergo their larval stage in spring, we now have a good idea of how old the individual is.

Contrary to primary scales, who have the same age as the fish, replacement scales have been grown further along the fish’s life cycle and are thus lacking the right number of annuli rings to correspond with the fish’s age. These are recognized by a much larger central plate than that found on the primary scales. Replacement scales can still show good annuli and growth patterns after they started growing, but since it is impossible to figure out exactly when in the fish’s life cycle that was, they are disregarded when it comes to age estimations. Certain other fish species, like brown trout, *Salmo trutta*, have very clear annuli, while cod, on the other hand, often have quite unclear and narrow annuli, often made of no more than 2-3 narrow sclerites. This can make age estimation through cod scales more challenging than in other species.

After selecting primary scales of good condition, the scales needed to be cleaned. When the scales are scraped off with a knife in the field, it is not uncommon that a little piece of skin, and other sorts of dirt is attached to the scale. This needs to be removed before the scale can be read. In the laboratory this was done by soaking the scales in a small container with a weak solution of green soap and tap water. The skin and dirt were then scraped off using fingernails and plyers. Scales were then dried and placed between two microscope slide glasses that were glued together and then photographed under a Leica S9i loupe and photographed using the LASX software. The contrasts in the photographs were enhanced to show the annuli rings more clearly.

Since 2021, 110 sampled individuals produced viable scales for age reading. Added to the 84 individuals whose age and length at age was estimated by Craig in 2021, makes a total of 194 viable scale samples out of a pool of 248 sampled cod. There are two explanations as to why there are no scale data from the remaining 54 individuals. 1) Because for whatever reason, there might not have been sampled scales from that fish in the field, or 2) all the sampled scales turned out to be replacement scales and thus not viable for a complete age determination process.

Between one and three scales from each individual cod was prepared and photographed, depending on the availability of high-quality primary scales. For each fish, the best quality picture with the clearest annuli rings was chosen to be used in age estimation and back-calculation of length at age. For this, the photographed scales were loaded into the measuring tool ObjectJ, a plug in in the program ImageJ. Otholits_1.11.0jj, a macro in ObjectJ was also used. This macro is designed to estimate the age of fish using picture of otoliths but can also be used on fish scales (figure 7). The macro measures the diameter of the scale's central plate, the distance from the central plate to the edge of the scale as well as the location of the annuli rings in increments related to the distance from the central plate and the edge of the scale (figure 7). The output from ImageJ was then transferred to an excel spreadsheet where age and length at age was calculated.

In theory, the fish's age is equal to the number of annuli rings on the scale. This is true to a certain extent. The annuli closest to the edge of the scale was formed during the latest winter season the fish lived through. Depending on how long time has passed since the latest winter when the scale is sampled, the distance from the last annuli to the edge of the scale will vary. Cod caught in the spring, (March or April) will not have experienced warm enough ambient water temperatures to increase their growth rate that year. The faster summer growth that gives wide sclerites in the scales and result in a paler scale section has thus not yet started, leaving the annulus ring of the season just short of being fully formed. Individuals caught in spring are almost a year older than what the scale readings seem to show. This was accounted for in the calculations by adjusting the plus growth, meaning the increment that spans the distance from the last annulus ring to the edge of the scale, to zero for all individuals caught during the spring months.

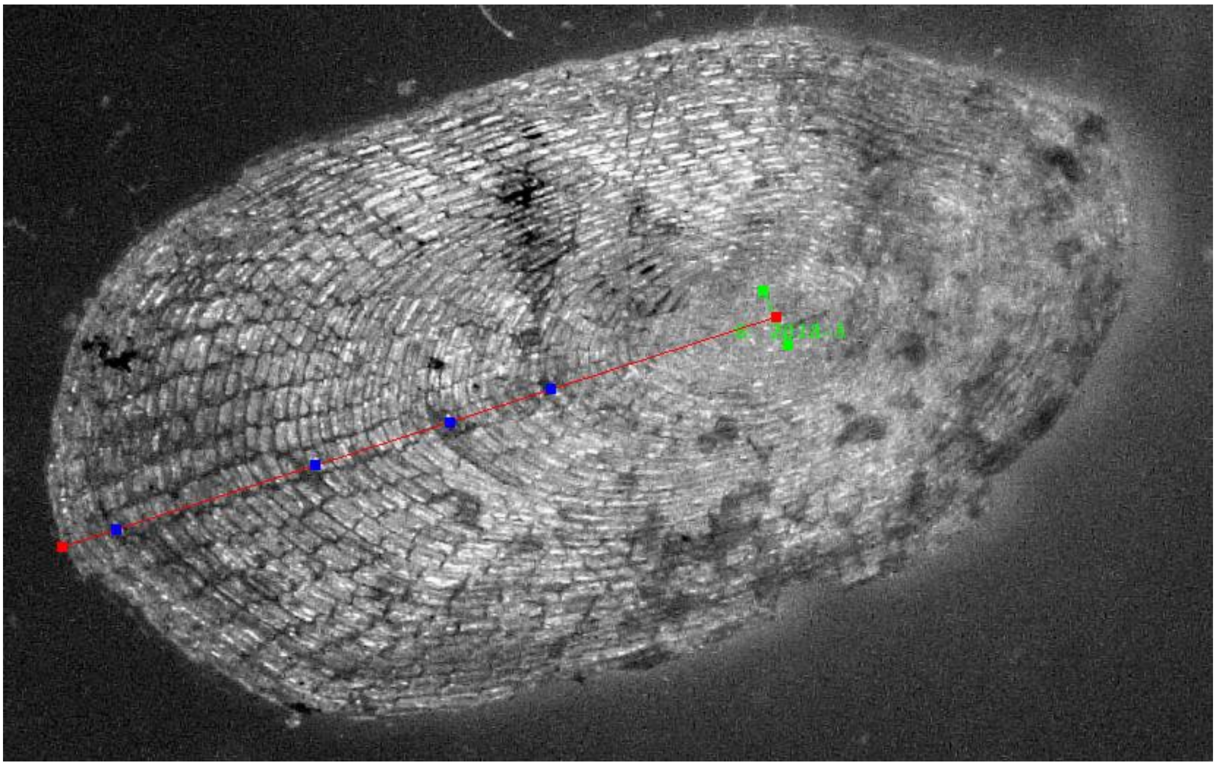


Figure 7. Screenshot of a cod scale in ImageJ using the macro Otholits_1.11.0jj. to estimate age. The green line (between the two green dots) is the diameter of the central plate. The red line (between the two red dots) is the distance from the center of the central plate to the edge of the scale. The four blue dots are placed at the annuli rungs and represent the increments at which the cod grows each year. This individual was caught in the fall and is four years old.

After back calculating the length at age for all the cod with viable scale samples it became apparent that there was a huge variation in the results. Particularly, the length at the first year showed large gaps between the upper and lower limits for the individuals sampled in 2021 and 2022. These one-year-olds ranged from 24cm to just below 6 cm with an average of 11.7 cm. Especially those small sizes caused doubts towards the reading methods in ImageJ and ObjectJ. Upon examining the literature, it became apparent that others have back calculated the age of one year old Norwegian cod to be between 9 cm and 26 cm long (Craig, 2021; Aalvik et al., 2015; Aalvik, 2013) Based on that, I decided to revisit the scale samples that fell outside of this range, which exclusively were on the smaller side, and conduct the scale reading on these samples anew.

Quantitative analyses

All quantitative analyses and plotting were conducted in R (R Develpoment Core Team, 2022) by using the R studio software. Most results in this thesis are presented as either boxplots or violin plots, with summary statistics such as mean and standard error or standard deviance, included. Differences among groups were inferred from these plots rather than performing statistical testing or model fitting. In order to explore if length-adjusted weight differed between sample zones and/or sample areas (inner fjord vs Drøbak) candidate linear models with variants of zone, area, body length as additive or multiplicative predictors were fitted and subjected to model selection using Akaike's information criterion. In these linear models, both body weight (the response) and body length (predictor) were ln-transformed to secure variance homoscedasticity.

Instantaneous mortality was estimated by applying the catch-curve method on the age-structure data using the Catch Curve-procedure in the FSA-package in R (Ogle et al., 2022).

Results

Catch per unit effort.

There was a lot of spatial and temporal variation in CPUE in the inner fjord area, making it hard to discern any patterns and tendencies (figure 8). Across all nine sampling rounds, zone 1 came out as the zone with the lowest CPUE values in eight of them (figure 8). Only in October 2022 did zone 3 have the lowest CPUE. Zone 2 had the highest CPUE values out of all three zones for all nine sampling rounds, except perhaps for December 2020 where zone 3 had higher catch yields (figure 8). Zone 3, the most secluded zone inside the Bærum basin yielded relatively even CPUE values between those in zone 1 and 2, with its highest CPUE in December of 2019 and 2022 (figure 8).

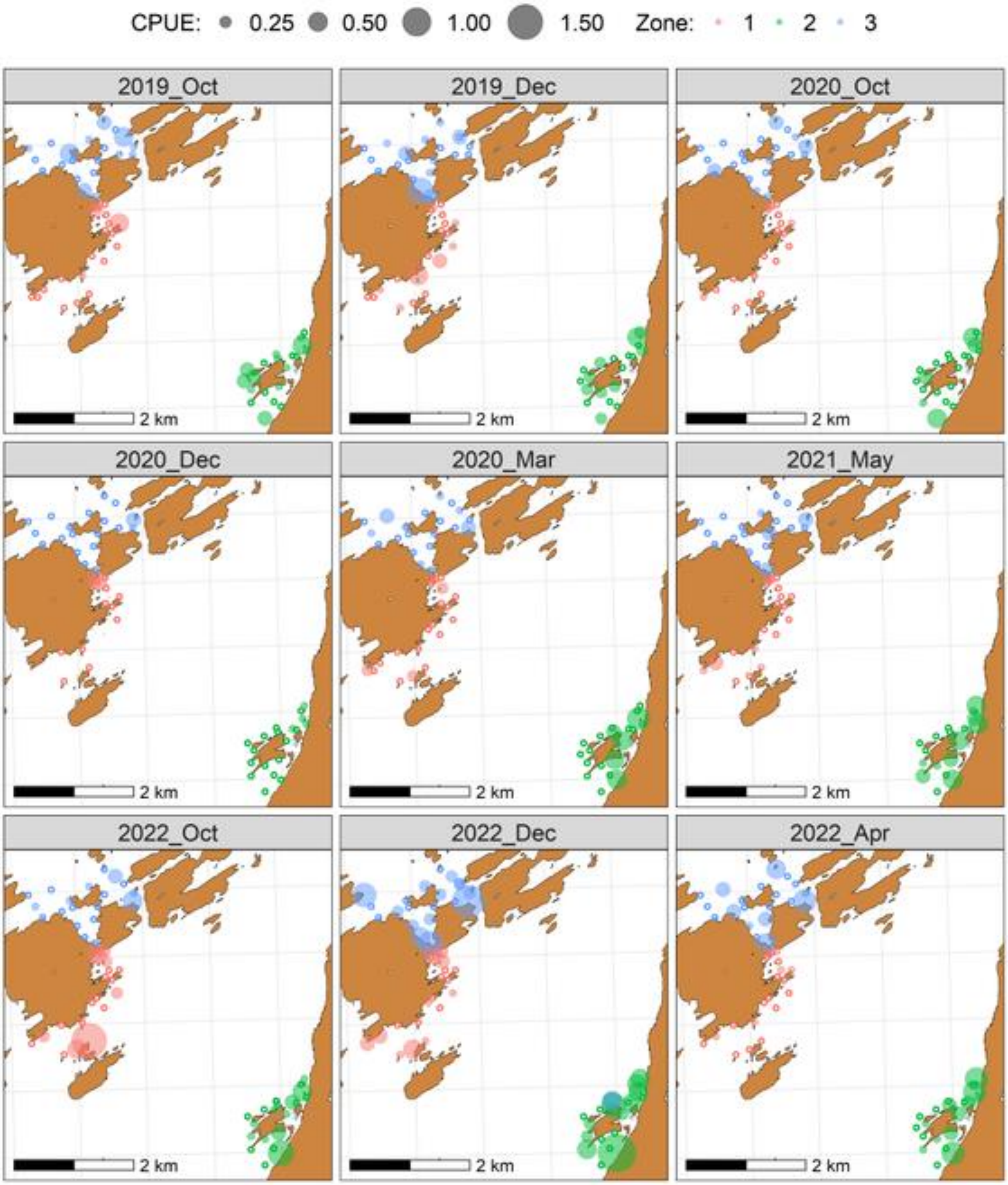


Figure 8. Catch per unit effort (CPUE), measured in number of cod caught per trap per 24 hours, for zones 1, 2 and 3 and all sampling rounds between 2019 and 2022. The larger the colored circle, the higher the CPUE. Hollow circles represent CPUE values of zero.

For both zones in the Drøbak area (North and South), CPUE was clearly highest in 2021 (figure 9). Similarly, CPUE was clearly highest in zone South for both years. For zone North, the decline in CPUE from 2021 to 2022 was quite extreme (figure 9). No seasonal variation can be stated as all sampling was conducted in September for both years and zones.

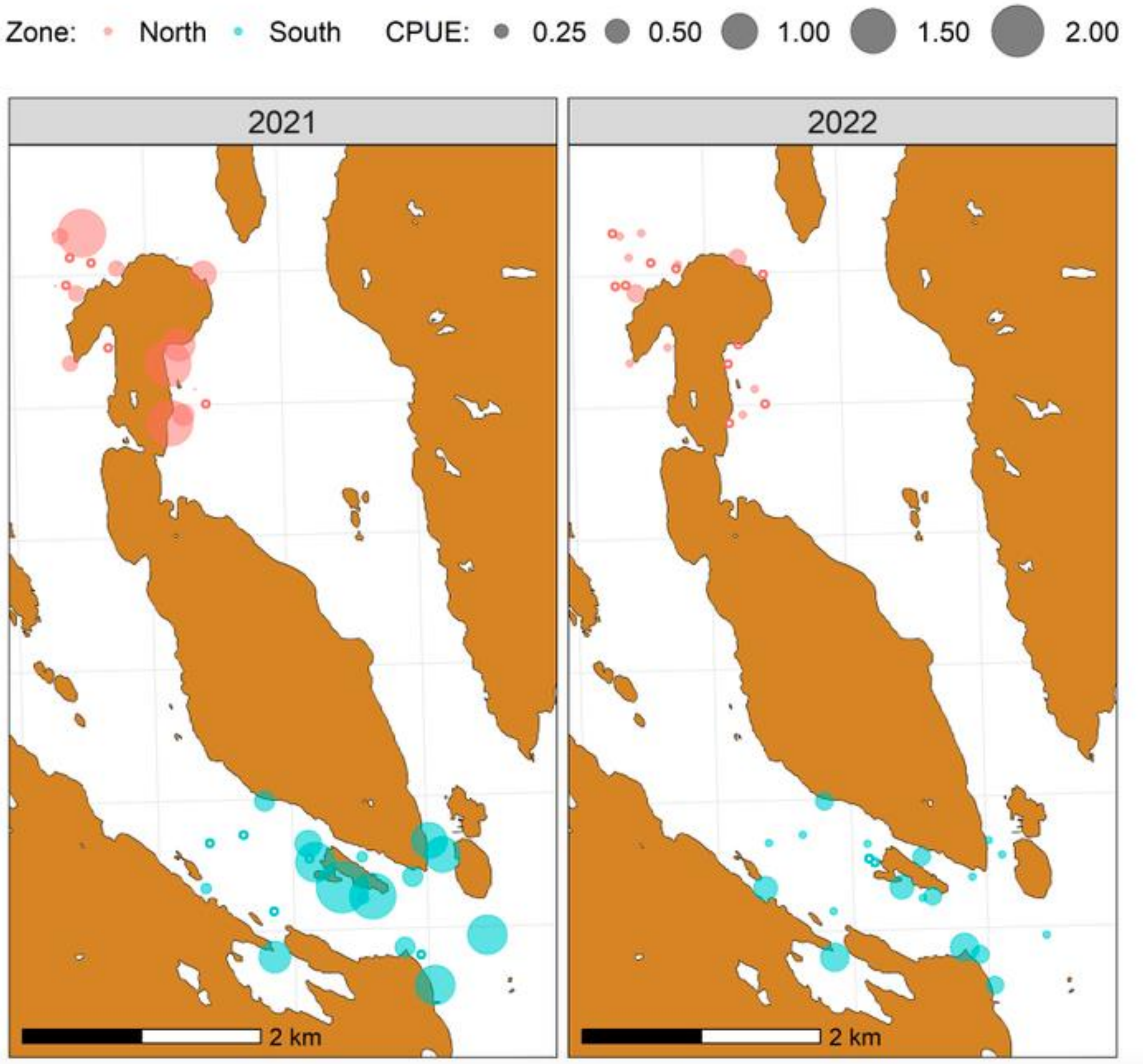


Figure 9. Catch per unit effort (CPUE), measured as number of cod caught per trap per 24 hours, for zone North and South in September 2021 and 2022. The larger the colored circle, the higher the CPUE. Hollow circles represent CPUE values of zero.

There is little development in CPUE in the three inner fjord zones (zone 1, 2, and 3) from 2019 to the spring of 2022 (figure 10). For the sampling rounds in the fall of 2022 both maximum and mean CPUE was higher than previous years and seasons. The number of instances with no cod catches were also lower here (figure 10). CPUE levels of 0 was, however, the most common type for all inner fjord zones.

Sampling in the two Drøbak zones (zone North and South) in 2021 yielded the highest CPUE out of the whole study (figure 10). These CPUE values did not, however, continue into 2022, where CPUE was similar to the inner fjord zones. Zone South in 2022, did, on the other hand have the least instances of no cod catches in the study (figure 10). Zone North in 2022 had very low CPUE and had the second lowest CPUE from 2022. Zone South had the highest CPUE among the two Drøbak zones for both years of sampling in that area (figure 10).

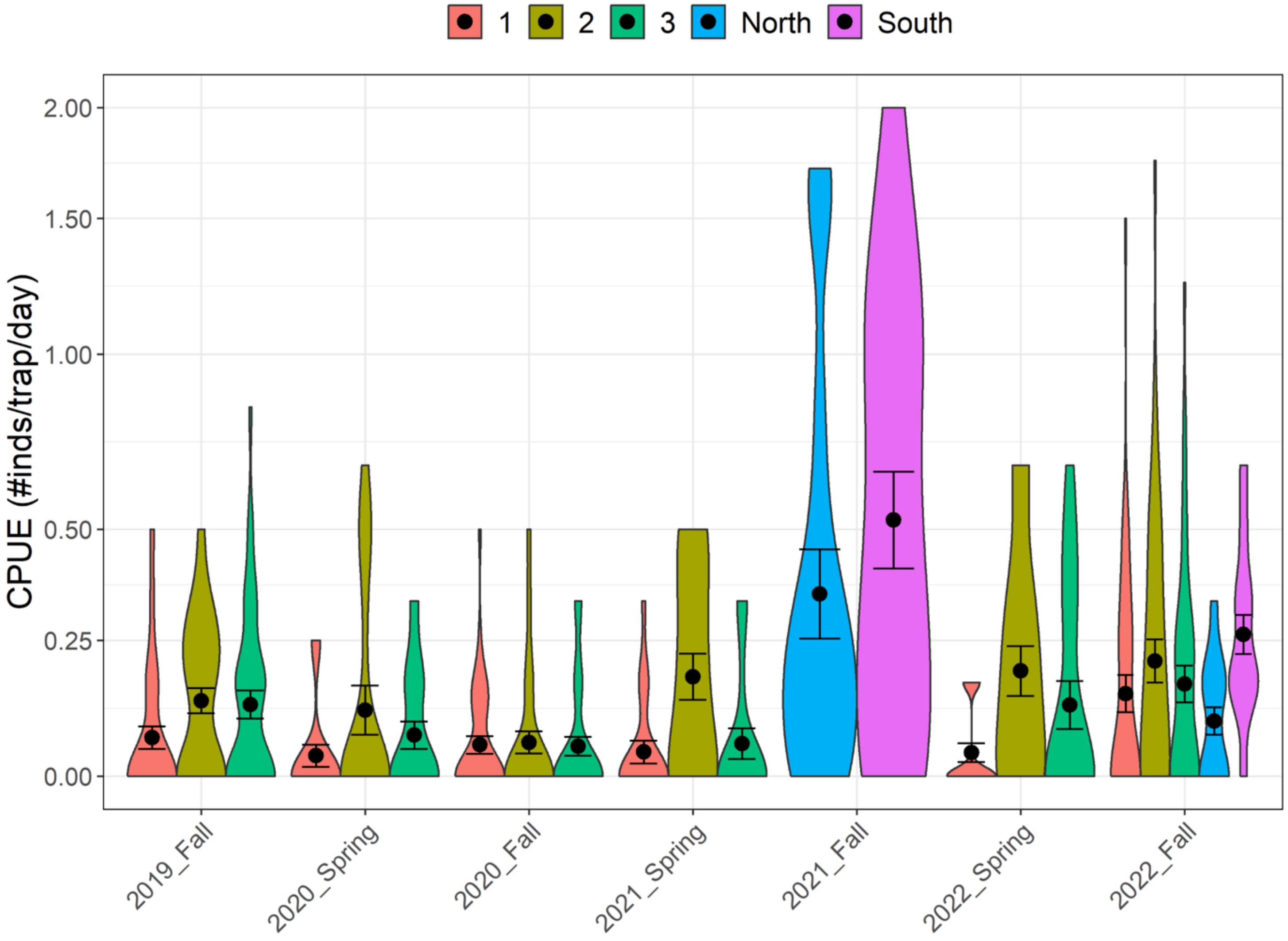


Figure 10. Violin plot showing the CPUE for each zone across seasons. The months March-May fall into the season "Spring," while the months August, September, October, and December fall into the season of "Fall." The violin's width indicates the number of times the respective CPUE value has occurred that season. The black dots represent the mean.

Condition factor.

The condition factor of the Oslofjord cod was clearly higher for cod in the Drøbak zones than those in the inner fjord area (figure 11). Figure 11 shows condition factor of all cod with a length above 30 cm that were caught during fall sampling rounds. As there were no sampling round in the inner fjord zones in the fall of 2021, this period is not represented in this figure. Condition factor of the Drøbak cod is higher than for the inner fjord cod. The cod with the highest condition factor altogether was caught in zone North in the Drøbak area in 2022, but apart from that it is hard to state any clear tendency in the Drøbak area across the two years of sampling (figure 11).

In the three inner fjord zones however, there is evidence of substantial among-year variation. Although condition factor has not changed much since 2020, it has dropped drastically from 2019 to 2022. There is, however, very little evidence of any variability between zones in the inner fjord (figure 11).

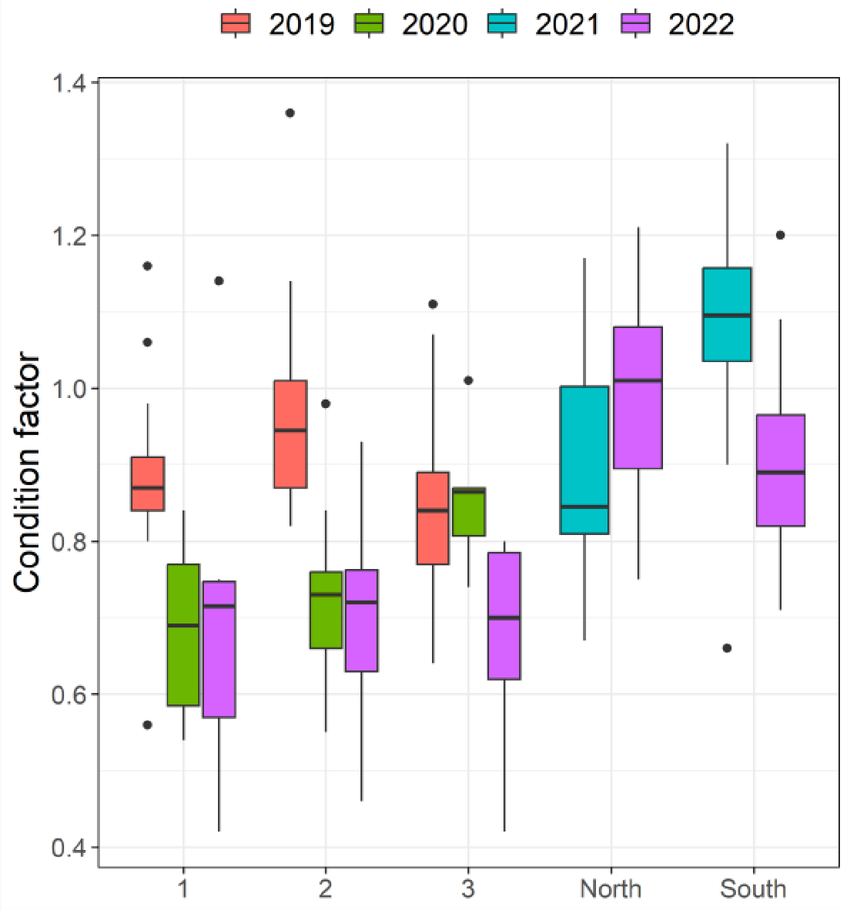


Figure 11. Boxplot comparing condition factor of cod caught in the Drøbak area (first two from right) and cod caught in the inner fjord area (last three from right) during fall sampling rounds. There was no sampling during fall of 2021, and thus no data from that period in this figure.

Despite Drøbak cod generally having higher condition factor, they were also much shorter than cod from the inner zones (figure 12). Yet, when cod from Drøbak and the inner fjord zones had the same length, the Drøbak cod tended to be heavier.

Drøbak cod have their highest condition factors while being short, and experiencing lower condition factors as they grow in length. The opposite may perhaps be said about cod from the inner fjord zones, as their condition factor seems to increase with length (figure 12).

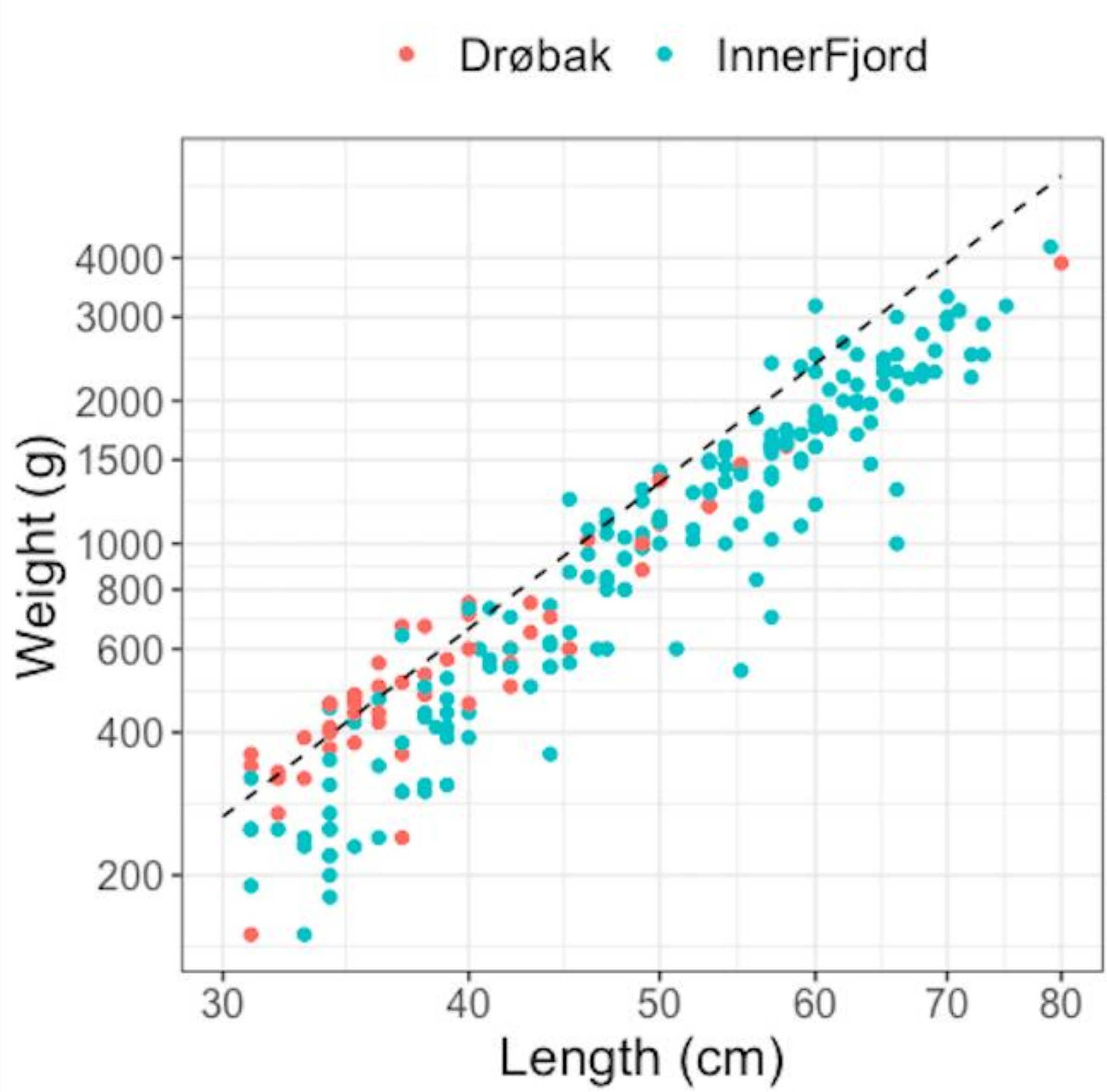


Figure 12. Linear regression on a logarithmic scale comparing the relationship between length (cm) (X-axis) and weight (g) (Y-axis) between cod from the Drøbak area (red) and cod from the inner fjord area (blue).

Model selection among candidate linear models modelling fall-period ln(weight), favored an interaction between year and ln(body length) and an additive effect of study area (Drøbak vs inner fjord) as predictors (ln(BL)*YR+StudySite, (table 1). The additive study area effect was highly significant, whereas the interaction effect between ln(BL) and year was boarder line significant (table 2). The selected model predicted for the only year with comparable fall data (2022) that similarly sized individuals in the Drøbak area to be heavier than those from inner fjord (figure 13).

Table 1. Model selection metrics for candidate models fitted to fall cod ln(weight)-data from inner Oslofjord during 2019-2022. K= number of parameters; AICc = corrected AIC, ΔAIC =difference between a candidate model's AIC and the AIC value of the candidate model with lowest AIC; ModLik = the model likelihood (amongst all candidates fitted); AICwt = the relative AIC-support amongst all fitted candidate models; LL = log-likelihood (deviance).

Model structure	K	AICc	△AICc	MocelLik	AICcWt	LL
ln(BL)*YR+StudySite	10	-30,681	0	1	0,393	26,05
ln(BL)*YR*StudySite	11	-29,863	0,819	0,664	0,261	26,788
ln(BL)+Zone+YR	10	-28,88	1,802	0,406	0,16	25,15
ln(BL)*StudySite+YR	8	-28,608	2,074	0,355	0,139	22,762
ln(BL)*Zone+YR	14	-26,452	4,229	0,121	0,047	28,617
ln(BL)*YR	9	-16,383	14,298	0,01	0	17,768
ln(BL)*Zone*YR	27	-12,168	18,513	0	0	38,562
ln(BL)*StudySite	5	11,095	41,776	0	0	-0,36
ln(BL)+StudySite	4	11,939	42,62	0	0	-1,845
ln(BL)	3	25,061	55,742	0	0	-0,456
intercept	2	365,406	396,087	0	0	-180,666

Table 2. Parameter estimate and effect test table for the selected model fitted to fall cod ln(weight)-data from Inner Oslofjord during 2019-2022. Est = parameter estimat, SE = standard error; DF = degrees of freedom, SS = sum of squares; MSS= mean sum of squares; F = Fischer's test statistics; p-value=significance level. YR=year, BL = body length; IF = inner fjord.

Parameter estimates

Parameter	Est	SE
Intercept[2019]	-3.54	0.73
ln(BL)	2.76	0.18
YR[2020]	0.16	0.92
YR[2021]	0.64	1.03
YR[2022]	-1.50	0.88
StudySite[IF]	-0.25	0.06
ln(BL):YR[2020]	-0.13	0.23
ln(BL):YR[2021]	-0.24	0.27
ln(BL):YR[2022]	0.32	0.22

Effect test

Effect term	DF	SS	MSS	F	p-value
ln(BL)	1	74.804	74.804	1653.866	<0.0001
YR	3	2.892	0.964	21.3139	<0.0001
StudySite	1	0.533	0.533	11.7762	<0.0001
ln(BL)*YR	3	0.366	0.122	2.6996	0.047

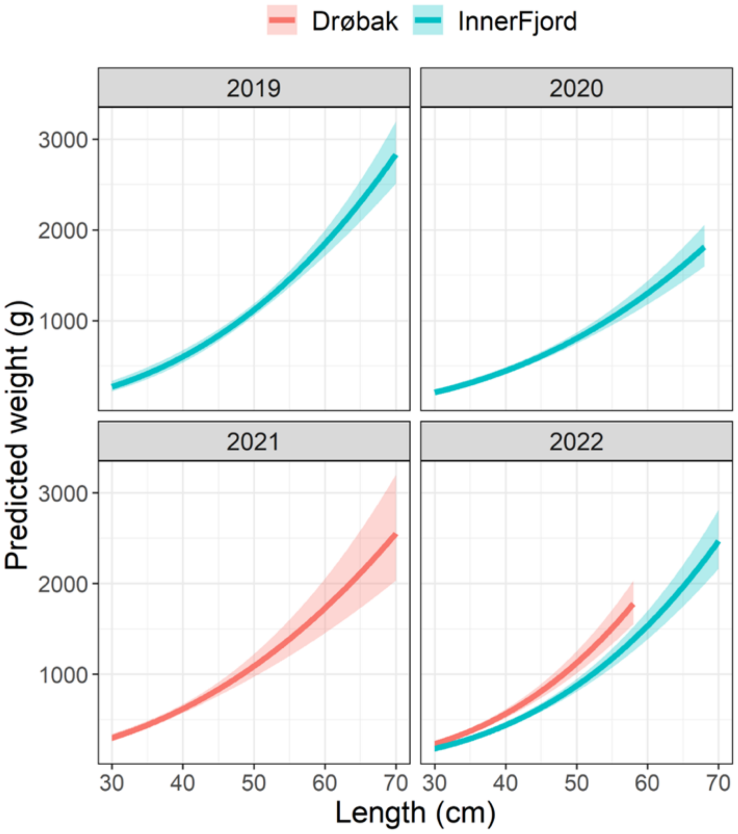


Figure 13. Prediction plot of length-specific weights for cod from the two study areas in inner Oslofjord during 2019-2022. Predictions were estimated from the selected linear model presented in Table 2 and only length intervals covered by data were plotted. Shaded areas represent 95 % confidence bounds.

Back-calculated length at age from scale readings

The most obvious finding is that the fish grow with age (figure 14), and that the rate of which they grow subsides around the age of 4 or five. Meaning that the cod, both from the inner fjord area and Drøbak area grow fastest the three first years of their life.

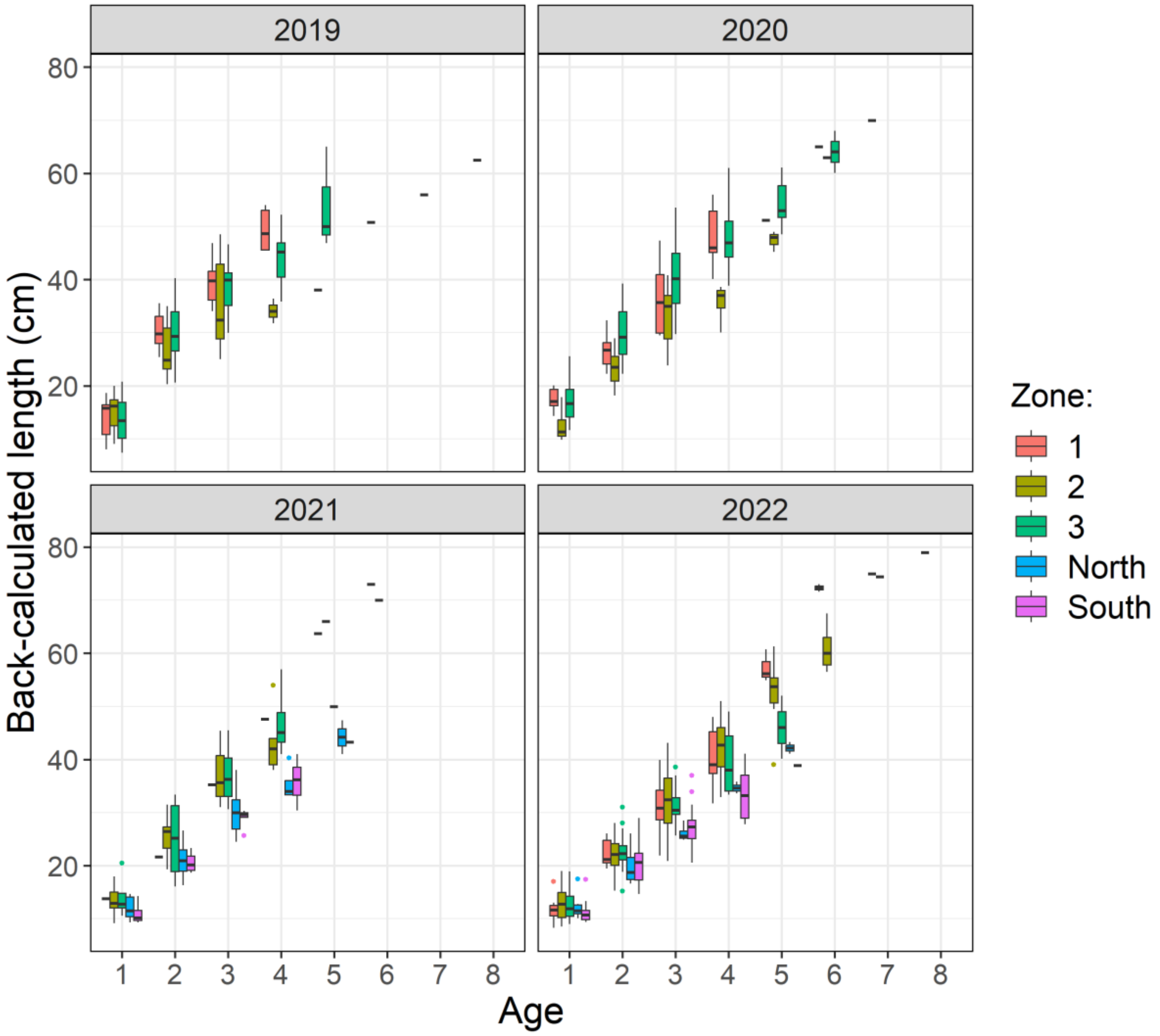


Figure 14. Four-faceted boxplot comparing the back-calculated length-at-age for the 194 cod who produced viable scale samples. Each facet shows the length-at-age as a proxy for growth rate for the individuals caught that year. The different sampling zones are separated by different colors.

As was stated before (figure 12), cod caught in the two Drøbak zones, both grow slower and are shorter than cod of the same age in the inner fjord zones (figure 14).

Additionally, there is evidence of a tendency that the size of any given age group in any given zone decreases over time since 2019. It would, for example, seem that three-year-old cod caught in zone 1, on average were the longest in 2019, and the shortest in 2022 (figure 14).

Figure 15 shows that the back calculated length for cod caught in 2019 and 2020 were between 10 and 20 cm long. However, the cod caught in 2021 and 2022 showed the back-calculated length at year one to be between 10 and 15 cm. There was a lot of overlap between these two groups, yet the mean length for one year old cod seems to have dropped over the last few years.

Again, it becomes evident that the cod caught in Drøbak were shorter than those from the inner fjord area, even as one-year-olds (figure 15).

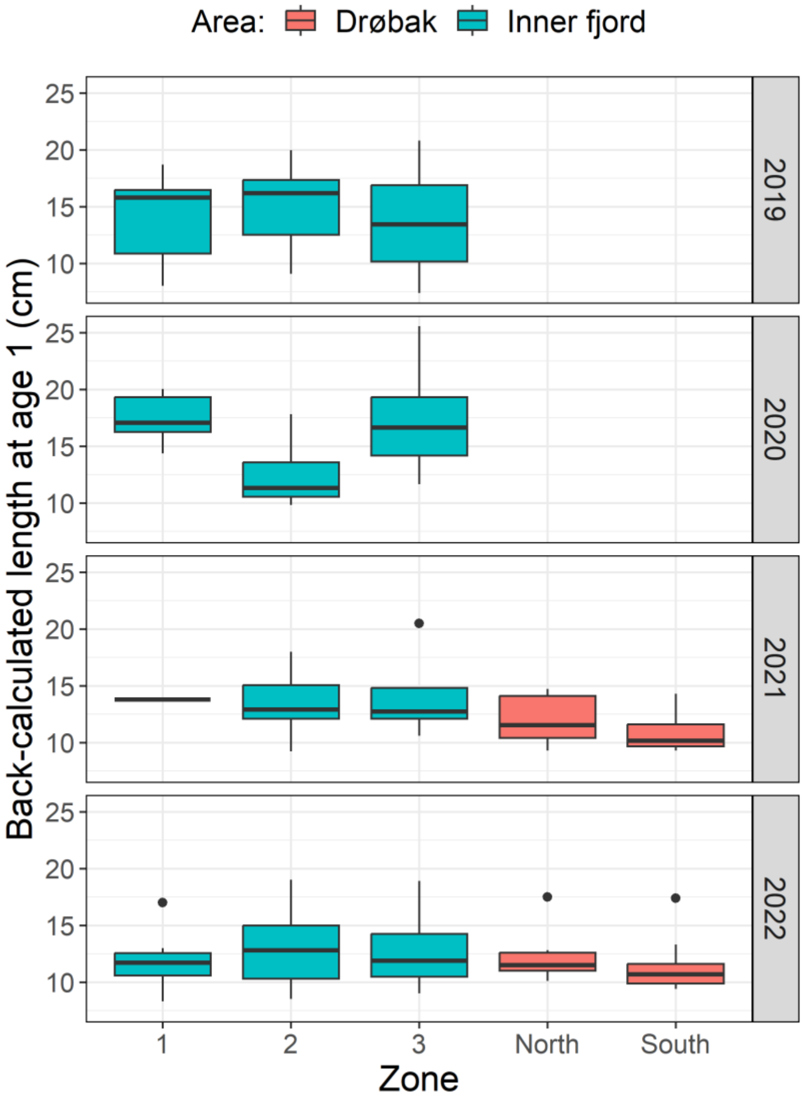


Figure 15. Four-faceted boxplot comparing the back-calculated length for one-year old cod divided by catch year (facets) and zones. Cod from the Inner fjord area/ zones 1, 2 and 3 are blue, while cod from the Drøbak area/ zones North and South are red.

Model selection among candidate models fitted to explain variation in back-calculated length at age 1 (L1) favored a simple model with just study area (i.e., inner fjord vs Drøbak) as the sole predictor (Table 3). This model attained 45 % of the AIC-support in the data and had 1.83 AIC-units lower than the second-most supported model (area+cohort). The most supported model predicted L1 to be 11.67±0.49 (SE) cm for Drøbak cod and 13.81±0.26 cm for inner fjord cod, which was significantly different from each other (one-way anova: $F_{1,185}=14.706$, $p<0.001$).

Table 3. Model selection metrics for candidate models fitted to explain variation in L1. K= number of parameters; AICc = corrected AIC, ΔAIC =difference between a candidate model's AIC and the AIC value of the candidate model with lowest AIC; ModLik = the model likelihood (amongst all candidates fitted); AICwt = the relative AIC-support amongst all fitted candidate models; LL = log-likelihood (deviance).

Model structure	K	AICc	△AICc	MocelLik	AICcWt	LL
Area	3	964,26	0,00	1,00	0,45	-479,07
Area+cohort	4	966,09	1,83	0,4	0,18	-478,94
Zone	6	966,28	2,02	0,36	0,16	-476,91
Area*cohort	5	967,63	3,37	0,19	0,08	-478,65
Zone*cohort	11	968,02	3,76	0,15	0,07	-472,26
Zone+cohort	7	968,35	4,09	0,13	0,06	-476,86
cohort	3	974,32	10,05	0,01	0,00	-484,09

Small cod ≤ 30 cm

It is important to state that back calculating the length at age for cod was mostly done on larger than 30 cm individuals. Six out of 194 individuals whose scales were studied, were below 30 cm. Three of these measured between 22 cm and 24 cm and were estimated to be one-year-olds. Two measured between 26 cm and 29 cm and were estimated to be two-year-olds. The last was a three-year-old and measured 29 cm.

The total number of small cod that were caught in 2019 and 2020 was just below half the number of cod that were above 30 cm and thus were tagged and sampled from. The fact that only one round of sampling was conducted in 2021 in the inner fjord zones may explain catch numbers of about half the numbers obtained the previous two years, yet the relationship between large and small cod catches remained roughly the same. In 2022, however, the number of small cods caught was not only larger than the number of larger cod, but vastly larger than the number of small cod caught in 2019 (288% more) (table 4).

In the Drøbak area, however, the number of small cod caught, far surpassed the number of larger ones in 2021, but did not carry over into 2022 where only 41% of the catches consisted of small cod (table 4).

Table 4. The total number of cod measured above 30 cm in length caught per year compared to the total number of cod measured below 30 cm in length caught per year.

		Inner Fjord			Drøbak
Year	Larger than 30 cm	Smaller than 30 cm		Larger than 30 cm	Smaller than 30 cm
2019	52	25			
2020	52	19			
2021	24	9		35	86
2022	59	97		26	18

Age distribution, cohort strength and mortality

While sampling in the inner fjord zones in 2019 and in Drøbak in 2021 and 2022, the most common age group to be caught in the cod traps were three-year olds, who have an average length of about 35 cm (figure 16).

Sampling in the inner fjords during the three years following 2019, four-year olds were the most common age group to be caught in the fyke nets (Figure 16). Figure 16 does, however, only use data from the fish who provided scale samples for age reading. Cod smaller than 30 cm were not further sampled, but may, in the larger instances, have reached the age of three years.

There is also evidence of a spatial difference in age composition in the inner fjord zones. In 2019 and 2020, the majority of the larger cod specimen were caught in zone 3, the innermost zone in the Bærum basin. In the two later years most of the largest, and oldest specimen were caught in zone 2.

In Drøbak, no cod older than five were caught, indicating this as the maximum age in this area. The majority of these five-year-olds were caught in zone North for both years.

Although there were individuals older than five in all years in the inner fjord, there is a considerably higher number of 5+ year old cod found among those caught in 2022 and they comprised almost one third of the entire catch (32 %) (figure 16).

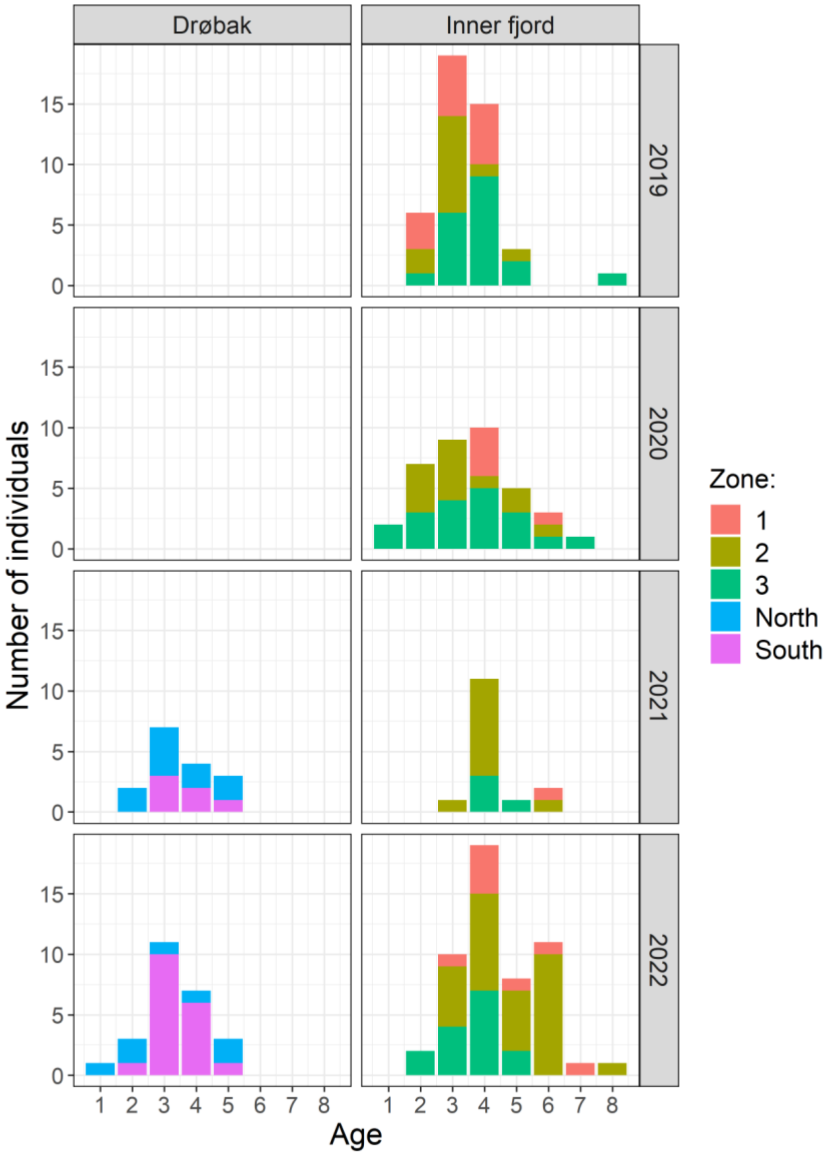


Figure 16. Faceted histogram comparing the estimated age group sizes in the Drøbak area (left) and Inner fjord area (right) over time (vertical facets). Each zone is separated by color.

The Oslofjord cod cohorts all decrease in size with time and age as older individuals die (figure 16). Figure 16 shows how a strong cohort continues to be strong as they age. In the inner fjord zones in 2019, This cohort consisted of three-year-old cod, four-year-old cod in 2020, and six-year-olds in 2022.

Instantaneous mortality for cod in the inner Oslofjord was highest before, and at the time of the fishing ban (2019). Mortality dropped, yet not by much, over the next three years (2020-2022) in the inner fjord zones. In Drøbak, the mean instantaneous mortality over the last two years of sampling (2021 and 2022) was the lowest of all three (table 5).

Table 5. Instantaneous mortality rate for cod in the Oslofjord just before and after the ban of cod fishing in the summer of 2019. Z= instantaneous mortality rate and SE= standard error.

Area	Period	Z	SE
Drøbak	After	0,576	0,038
Inner fjord	After	0,596	0,166
Inner fjord	Before	0,614	0,138

Discussion

Catch per unit effort in the inner Oslofjord following the catch ban.

It is little evidence to support that the cod population in the inner Oslofjord has recovered significantly over the four years since the implementation of the catch ban in 2019. Cath per unit effort for the three inner fjord zones, zone 1, 2 and 3, increased marginally in 2022, but overall cannot be said to have increased much since the publication of Craig (2021). This indicates an alarming, yet not surprising reality where the cod population in the inner fjord zones, for whatever reason is struggling to recover. On the other hand, higher abundances of older cod specimen have been observed in the inner fjord area in 2022, indicating the potential star of a population recovery.

With a higher CPUE in the Drøbak area than in the inner fjord zones, I believe there is a higher population density of cod there, with the highest density in zone South, the zone closest to the fjord sill and the outer Oslofjord. The highest CPUE in Drøbak (zone South in 2021) (0,52 ±0,58) was twice as high as the highest CPUE from 2011 and 2012 (0,31 ±0,23).

When sampling, none of the tagged individuals were recaptured in one of the other zones from where it was originally tagged (appendix 1). Combine this with the previously measured, relatively small home range of coastal Skagerrak and Oslofjord cod (less than 3 km^2) (Bøe, 2014; Ilestad et al., 2012; Aalvik, 2013), it is quite unlikely that there is continuous interaction between these two areas that are 11-15 km apart. Cod from the inner fjord zones and the Drøbak area can arguably be considered two separate but perhaps not independent, populations who face separate challenges and react differently to the catch ban, and should then be assessed separately.

In the early stages of this thesis, there was a hope to use the mark-recapture model to estimate relative population size of the cod in the inner Oslofjord and the Drøbak area. This method relies on a decently high recapture rates to produce good and reliable results. In my case, recapture numbers were too low, but not by much (ranging between 6.5% and 14.3%). Low recapture rates are often occurring when sampling from large populations, as the marked individuals have a large number of non-tagged individuals to disperse amongst. In this situation, all evidence points to the contrary, that the cod population in the inner Oslofjord is small rather than large. Another possible reason for low recapture rates can be high mortality in the sample population or high emigration out of the sample area. Both are plausible situations for the Oslofjord cod. High natural mortality can very likely hinder recovery of the population. The fact that this study found an increased abundance of older cod (5–8 year-olds) in the inner fjord zones in 2022 indicate somewhat lower mortality than previous years. Recapture numbers are still too low to estimate this but may increase in the future, given the continuation of the catch ban. Others have also speculated that in more recent years, cod only roam through the inner fjord area rather than being stationary like they were before the collapse (Espeland & Knutsen, 2023; Knutsen et al., 2022; Moland et al., 2021).

Due to the lack of appropriate recapture data, other methods for population estimates had to be utilized. Catch per unit effort was a well-suited method for this research. It allows for comparisons with previous studies (Craig, 2021; Ski, 2013) who used the same or similar methods. Catch per unit effort (CPUE) was here measured as the mean number of cods caught per fyke net trap per day. As long as the same catching method is used (fyke nets), they are checked with the same time interval (every second day) and stay at the same location for the same amount of time (one week), then all samples are directly comparable.

In this instance, the CPUE data cannot be used to estimate the population size of cod in the inner Oslofjord in terms of number of individuals. It can, however, estimate population size in comparison to other regions or earlier years. Compared to CPUE levels from 10 years ago (Ski, 2013), the current cod population is likely much smaller than in 2012. This is, of course, no big surprise, as this decline in the cod population is what triggered the fishing ban in the first place. The question is whether there have been any changes in cod CPUE since then. Both my and other’s results indicates that, no. There is no change in catch per unit effort, which means there is no indication on neither more nor less cod in the inner fjord than in the summer of 2019 (Espeland & Knutsen, 2023; Haugen et al., 2023; Knutsen et al., 2022; Moland et al., 2021). Which, of course, begs the inevitable question. Why? Why are the cod population in the inner Oslofjord not recovering?

One, already touched upon possibility, is that the inner Oslofjord following the near extinction of the native population around 2010 and the following years, no longer is home to a permanent cod population. It is possible that cod from the outer Oslofjord and Skagerrak simply pass through the inner fjord to feed but do not spawn here. No spawning would inhibit recovery. This theory is supported by the absence of young-of-the-year cod in beach seine surveys the last three years (Espeland & Knutsen, 2023) and the absence of cod larvae in the inner Oslofjord in 2022 (Knutsen et al., 2022). The latter study did find seemingly contradictory results by also finding plenty of cod egg in the inner fjord, particularly in the Bærum basin (zone 3) (Knutsen et al., 2022). Perhaps the problem with cod recruitment does not lie in spawning, but in the survival of larvae and young fish through their first year. The theory that cod have migrated into the fjord is further supported by personal observations in the field where cod now tend to exhibit a more gray phenotype more common with the Skagerrak cod than with the more brown speckled specimen that used to inhabit the inner fjord years ago (Knutsen et al., 2022; Moland et al., 2021). Further studies looking into the genetics of the inner Oslofjord cod could be of use in this field.

This study also has imitated sampling reach. All cod traps were placed at shallower depths than 30 meters, and in close proximity to land (either islands or mainland). Perhaps the cod simply is not evenly dispersed through the inner fjord, but rather tend to congregate at certain sites, that just so happens to be outside of our sampling zones. Although possible, I consider this unlikely. It may also be likely that different methods show different tendencies over time. The previously mentioned beach seine sampling did, after 2010, not catch any 0-group cod in the inner fjord, something this study did. Not being able to catch a certain age group in one area with a given method, does not necessarily exclude the possibility of that age group being present in other nearby areas. Beach seine sampling occurs in shallow surface waters, which have warmed several degrees over the last years due to Global Warming. Cod are adapted to colder waters and larvae and young-of-the-year cod have the narrowest thermal window in the population (Oomen et al., 2022; Pörtner & Farrell, 2008). For this reason, young cod might simply avoid spending time in the warmer surface waters that the beach seine sampling occurs.

Another argument is that shallow waters just by the shore used to hold many attractive habitats for juvenile cod. Seagrass meadows and kelp forests are extremely vital marine habitats for a wide range of species. For a predatory species like cod, both juvenile and older individuals use such 3-dimmensional habitats as hunting grounds as well as hiding places from other predators. Because of the high population density along the Oslofjord and rising living standard, activities such as recreational boating becomes much more common over the last years. This inevitably led to more boats on the fjord and mor piers and small boat harbors for these boats. Such piers are often built in secluded bays and inlets, which, incidentally, is the same areas where seagrass meadows are common. Many of the Oslofjord municipalities also have an agriculture intensive area use, and fertilizers from this agriculture is swept into the fjord through runoff. This causes high amounts of CDOM in the fjord, which reduces visibility. Since seagrass and kelp are photosynthetic organisms, they rely on sun rays penetrating through the water column. As the euphotic zone gets shallower, and suitable areas are subject to construction and urbanization, these habitats dwindle in their range. With reduced rearing habitats for juvenile cod, in the shallower and warmer waters by the shore, it may be that the Oslofjord cod utilize other, deeper habitats.

The University of Oslo conducts a yearly scientific bottom trawl sampling round in a location by the islands Steilene, some 2 kilometers south of Zone 2 (Hylland & Holt, 2021). Back in 2014-2015 they would get around 40 cod per trawl. In 2017, just before the cod fishing ban was introduced, they caught no cod whatsoever. The last years they average around 10-15 cod per trawl. These numbers are not suitable for a comparison with my results in terms of numbers. One can, however, compare the overall tendencies, in which there are several similarities. It does seem like their catch tendencies for cod have improved more since the catch ban in 2019 than what my fyke net trapping has, allowing for the argument that cod tend to congregate in deeper waters in more recent years. Several factors may cause cod to dive deeper. As mentioned before, cod are adapted to cold water, and with a rapidly warming globe, surface waters are warming faster than the deeper layers. One could also speculate on the heightened boat traffic on the fjord has its effect. At least one previous study has shown that cod tend to be scared of boat engine sounds and dive deeper to avoid it (Martijn, 2021).

Mortality

Perhaps the most logical argument as to why the cod population in the inner Oslofjord has not recovered following the catch ban, is that the population has a high mortality. For most fish species, cod included, larvae and young fish can be said to be a bottleneck for recruiting the next generation (Palińska-Żarska et al., 2014; Sundby et al., 1989). If enough of the juvenile demographic in a population perish before they reach sexual maturity and spawn, there will be no recruitment to the population. It may be the case in the inner Oslofjord that juvenile cod are struggling to survive to maturity. This may be a result of the previously mentioned reduction of rearing and hunting habitats like seagrass meadows and macroalgae forests. Without these habitats, juvenile cod may likely struggle with finding enough food, and worse, hide from predators. The fish species dynamic and composition of the inner Oslofjord has changed over the last 10 year, and whiting, *Merlangius merlangus*, has become increasingly more dominant in recent years (Hesthagen et al., 2021). Closely related to cod, this fish species is a vicious predator whose larger specimen can reach 70 cm. Heavy predation on juvenile and young cod by a growing whiting population may be one of the reasons why the cod struggle to recover after the catch ban.

In the Drøbak area the cod seems to face somewhat different challenges related to mortality. Drøbak cod tended to be shorter than inner fjord cod at the same age (by around 2-4 cm) (figure 14 and 15). Additionally, no cod above the age of five was caught in the Drøbak area (figure 16). To me, that suggests fishing related mortality. As anglers tend to prefer larger fish and are more likely to release smaller specimen back into the wild. Fishing pressure has been shown to drive selection towards smaller individuals in harvested populations (Bianchi et al., 2000; Kuparinen & Merilä, 2007). It is my belief that the cod catch ban is either not conveyed well enough or not enforced properly, resulting in recreational anglers fishing for cod in the Drøbak area. The legal regulation that describes the cod catch ban states that one dispensation may be made. Rumors will, however, have it that several such dispensations have been made for commercial anglers. The extent of this needs to be investigated as it may have a not so insignificant effect on the recruitment and recovery of the cod population. Fishing effort on cod in the Drøbak area would certainly explain why they are both shorter at any given age and never seem to exceed the age of five.

On the positive side, instantaneous mortality decreased in the inner fjord zones from before the catch ban in 2019 (Z=0,614) to the three years after the catch ban (Z=0,596) but remained lowest in the Drøbak area (Z=0,576) (table 5). These estimates are quite similar and have overlapping confidence intervals and are likely explained by the increased abundance of older cod in the inner fjord zones in 2022. Although uncertain, this may indicate that the cod catch ban may have positive effects on cod recovery after all.

Condition factor

My results came to the alarming conclusion than the condition factor of the cod in the inner fjord zones has dropped since 2019. The same was thankfully not true for Drøbak cod, whose condition factor was higher than the inner fjord cod and showed high among-year variability but no sign of dropping. Poor condition factor in the inner fjord cod is likely one of the reasons the population struggles to recover. High physiological stress and low energy reserves may very likely have impacted both the cod’s fecundity and the number and size of the fertilized eggs. Condition factor is dependent on food intake and since cod feed in higher volumes and at higher frequencies in the summer (Fry, 1947), their condition factor fluctuates around the year. In the fall, after a summer of fast growth and high frequency feeding, condition factor in cod is generally at its highest.

As stated above, habitats like kelp forests and seagrass meadows in the inner Oslofjord have been severely reduced (Haugen et al., 2023; Rinde et al., 2021). Since these habitats are both feeding and hiding places for marine organisms like mollusks, crustaceans, and small fish, cod have used these areas as hunting grounds. It may simply be that because of habitat degradation, there isn't enough food for the cod in the inner Oslofjord anymore.

Food quality is also a potential focus regarding condition factor. Previous studies on Baltic cod have concluded that thiamine (vitamin B1) deficiencies in cod have a negative effect on condition factor (Engelhardt et al., 2020). This vitamin deficiency is likely also present in the inner Oslofjord cod populations as a result of poor quality, or change in food sources (Craig, 2021; Haugen et al., 2023). Thiamine, as well as other vitamins are produced by microbes in both the sediments and water column of marine ecosystems. These microbes are often sensitive to pollution, creating devastating cascading effects up the nutrient chain (Mantua et al., 2021). That is why I suggest more studies on the changing microbe composition in the inner Oslofjord and how it may affect vitamin supply to other trophic levels.

Marine parasites are extremely common, also on cod. In some instances, high parasite densities have resulted in both lower condition factor and halted recovery in Baltic cod (Mehrdana et al., 2014). In the inner Oslofjord, the parasite *Cryptocotyle lingua*, is commonly seen on cod during field sampling (Craig, 2021; Haugen et al., 2023). This parasite originate in the marine gastropod common periwinkle, *Littorina littorea*, and has seabirds as an end host (Stunkard, 1930), and is lodged in the fish's skin where it can be seen as a black spot (figure 17). Figure 17 shows a cod that was caught in the inner fjord zones in early May 2023. This individual is both sickly thin and full of the black spots indicating *C. lingua* parasitic infections. Although this individual is an example of the extreme, it showcases the increasingly poor condition of the inner Oslofjord cod population.

Figure 17. Two photographs of a cod caught in the inner fjord area in May 2023. This specimen is extremely thin and full of parasites. Potos: Jonathan Colman

Age composition and recruitment

There are also some positive tendencies in my findings. In 2022 in the inner fjord zones a larger part of the total catch consisted of individuals smaller than 30 cm (62 % of the total catch) (table 4) and individuals over the age of five (12 % of the total catch, and 32 % of the larger than 30 cm catch) (figure 15) than previous years. This indicates that although there is no evidence of increased cod density, the catch ban may still have positive effects on the population.

In the inner fjord zones in 2022 and in the Drøbak area in 2021, the majority of the total catch consisted of small cod below 30 cm. Back-calculated length-at-age and age estimation from scale samples of six cod below 30 cm indicates that these small cod may not be older than three years old, making them juvenile. One or two years of high juvenile catches does not make a trend, and hardly even a tendency, but there is evidence that there are more juvenile cod in the catch during the latest years of sampling. Despite large variations, this could indicate an increased recruitment in the population if these juveniles survive until sexual maturity and manage to spawn. If this high juvenile catch continues in fyke net sampling in future years, then this is a very positive outcome.

In the inner fjord zones, particularly zone 2, in 2022, there was also a large catch percentage of individuals of five years or more (32 %). Compared to previous years, this is highly positive. If the catch ban on cod allows inner Oslofjord cod to grow older, and closer to the national average maximum age for coastal cod (seven years) (Hesthagen et al., 2021), then the ban have some positive effects on the cod population in the inner fjord zones and the Drøbak area.

Conclusion

The cod catch ban in the Oslofjord from 2019 has not resulted in an increased abundance or density of cod, neither in the inner fjord zones, nor in the Drøbak area. Catch per unit effort was higher in the Drøbak area than in the inner fjord zones, and it seems the two areas experience different effects from the catch ban.

Several suggestions try to explain why cod struggle to recover after the catch ban, but explanations are complex and challenging and may include habitat reduction, climate change, heavy predation, and continued fishing despite the catch ban. In the Drøbak area, a maximum age of 5 years indicates continued fishing.

Condition factor in the Drøbak cod was higher than in the inner fjord cod where conditions have dropped since 2019. This may be due to thiamine (vitamin B1) deficiencies.

The catch ban does seemingly also have positive effects as more juvenile cod and individuals with a 5+ age, have been caught the inner fjord area in 2022 than previous years. Perhaps the catch ban allows for the possibility of improved recruitment and allowing cod to grow older.

My suggestions for further actions in the inner Oslofjord to further assist the cod populations is to maintain the catch ban, as it does have some positive effects, assess the extent of harvesting of cod from the fjord, either through dispensations or ignorance and improve the enforcement of the catch ban as only very limited fishing should be tolerated in a catch ban area. Additional improvement of general water quality in the fjord would undoubtedly lessen the stressors on the cod population, but water quality is a challenging and complex situation to deal with, and will likely require additional changes in limnic systems, agricultural practices, and handling of urban wastewater.

References

Abbott, J. K., Lew, D. K., Whitehead, J. C., & Woodward, R. T. (2022). The future of fishing for fun: The economics and sustainable management of recreational fisheries. *Review of Environmental Economics and Policy, 16*(2), 262-281.

Askeheim, S. (2021). *Drøbaksundet*. Retrieved 15.02.2023 from https://snl.no/Drøbaksundet

Bavington, D. (2011). *Managed annihilation: an unnatural history of the Newfoundland cod collapse*. UBC press.

Bianchi, G., Gislason, H., Graham, K., Hill, L., Jin, X., Koranteng, K., Manickchand-Heileman, S., Paya, I., Sainsbury, K., & Sanchez, F. (2000). Impact of fishing on size composition and diversity of demersal fish communities. *ICES Journal of Marine Science, 57*(3), 558-571.

Brander, K. M. (1994). Patterns of distribution, spawning and growhth in North Atlantic cod: the utility of inter-regional comparisons. ICES Marine Science Symposia,

Bryhn, A. C., Bergek, S., Bergström, U., Casini, M., Dahlgren, E., Ek, C., Hjelm, J., Königson, S., Ljungberg, P., & Lundström, K. (2022). Which factors can affect the productivity and dynamics of cod stocks in the Baltic Sea, Kattegat and Skagerrak? *Ocean & Coastal Management, 223*, 106154.

Bøe, K. (2014). *You are what you get caught with: inter-individual variation in coastal Atlantic cod behaviour* Norwegian University of Life Sciences, Ås].

Cooke, S. J., & Cowx, I. G. (2004). The role of recreational fishing in global fish crises. *BioScience, 54*(9), 857-859.

COSEWIC. (2010). *COSEWIC Assessment and Status Report on the Atlantic Cod Gadus morhua* https://www.sararegistry.gc.ca/virtual_sara/files/cosewic/sr_Atlantic%20Cod_0810_e1.pdf

Craig, D. C. (2021). *Cod on the dive: investigating Atlantic cod of the Inner Oslofjord during population decline* Norwegian University of Life Sciences, Ås].

Dannevig, A. (1933). On the Age and Growth of the Cod (Gadus callaris L.) from the Norwegian Skagerrack Coast. *Report on Norwegian Fishery and Marine Investigation 4*(1).

Dolven, J. K., Alve, E., Rygg, B., & Magnusson, J. (2013). Defining past ecological status and in situ reference conditions using benthic foraminifera: a case study from the Oslofjord, Norway. *Ecological indicators, 29*, 219-233.

Ellertsen, B., Solemdal, P., Strømme, T., Tilseth, S., Westgård, T., Moksness, E., & Øiestad, V. (1980). Some biological aspects of cod larvae (Gadus morhua L.).

Engelhardt, J., Frisell, O., Gustavsson, H., Hansson, T., Sjöberg, R., Collier, T. K., & Balk, L. (2020). Severe thiamine deficiency in eastern Baltic cod (Gadus morhua). *PLoS One, 15*(1), e0227201.

Espeland, S. H., & Knutsen, H. (2023). Rapport fra høstundersøkelsene med strandnot i indre og ytre Oslofjord 2022. *Rapport fra havforskningen*.

Forskrift om forbud mot fiske i gytefelt for torsk, (2019). https://www.fiskeridir.no/Yrkesfiske/Regelverk-og-reguleringer/J-meldinger/Gjeldende-J-meldinger/j-231-2022

Froese, R. (2006). Cube law, condition factor and weight–length relationships: history, meta-analysis and recommendations. *Journal of applied ichthyology, 22*(4), 241-253.

Fry, F. E. J. (1947). Effects of the environment on animal activity. Pub. Ontario Fish. Lab. No. 68. *U. Toronto Studies, Biol. Ser., 55*, 1-52.

González-Irusta, J. M., & Wright, P. J. (2016). Spawning grounds of Atlantic cod (Gadus morhua) in the North Sea. *ICES Journal of Marine Science, 73*(2), 304-315.

Goulletquer, P., Gros, P., Boeuf, G., & Weber, J. (2014). The importance of marine biodiversity. In *Biodiversity in the Marine Environment* (pp. 1-13). Springer.

Grabowski, T. B., Boswell, K. M., McAdam, B. J., Wells, R. D., & Marteinsdóttir, G. (2012). Characterization of Atlantic cod spawning habitat and behavior in Icelandic coastal waters. *PLoS One, 7*(12), e51321.

Gunnlaugsson, S. B., & Valtysson, H. (2022). Sustainability and wealth creation, but no consensus: Recent decades in Iceland's ITQ-managed fisheries. *Marine Policy, 135*, 104836.

Hallenstvedt, A. (2020, 11.08.2020). *Trål*. SNL. Retrieved 20.02.2023 from https://snl.no/trål

Haugen, T., O, Colman, J., & Moe, S., R. (2023). Torsk og hummer i inder Oslofjord: Effekter av vernetiltak. *MINA fagrapport, 83*.

Hesthagen, T., Weinerroither, R., Bjelland, O., Byrkjedal, I., Fiske, P., Lynghammer, A., Nedraas, K., & Straube, N. (2021). *Fisker: Vurdering av torsk Gadus morhua for Norge*. Artsdatabanken. https://artsdatabanken.no/lister/rodlisteforarter/2021/29760

Huggins, R. (1989). On the statistical analysis of capture experiments. *Biometrika, 76*(1), 133-140.

Hutchings, J. A., & Rangeley, R. W. (2011). Correlates of recovery for Canadian Atlantic cod (Gadus morhua). *Canadian Journal of Zoology, 89*(5), 386-400.

Hylland, K., & Holt, T., Fredrik. (2021). Fiskesamfunn i indre Oslofjord: Utvikling 2011-2021. *Åreberetning 2021 Fagrådet for vann og avløpsteknisk samarbeid i indre Oslofjord*, 27-33.

Haase, K., Weltersbach, M. S., Lewin, W.-C., Zimmermann, C., & Strehlow, H. V. (2022). Potential effects of management options on marine recreational fisheries–the example of the western Baltic cod fishery. *ICES Journal of Marine Science, 79*(3), 661-676.

Ilestad, A., Haugen, T., & Colman, J. (2012). Differential habitat use between adult European sea bass and North Atlantic cod in the inner Oslo Fjord: influence of abiotic environmental variables. *Advances in Fish Tagging and Marking Technology*, 265-288.

Kleiven, A. R., Fernandez-Chacon, A., Nordahl, J.-H., Moland, E., Espeland, S. H., Knutsen, H., & Olsen, E. M. (2016). Harvest pressure on coastal Atlantic cod (Gadus morhua) from recreational fishing relative to commercial fishing assessed from tag-recovery data. *PLoS One, 11*(3), e0149595.

Knutsen, H., Espeland, S. H., & Moland, E. (2022). Evaluering av tiltak for vern av kysttorsk i sør innført juni 2019. *Rapport fra havforskningen*.

Kuparinen, A., & Merilä, J. (2007). Detecting and managing fisheries-induced evolution. *Trends in ecology & evolution, 22*(12), 652-659.

Kurlansky, M. (1997). *Cod: a bibliography of the fish that changed the world*. Penguin Books.

Lindegren, M., Diekmann, R., & Möllmann, C. (2010). Regime shifts, resilience and recovery of a cod stock. *Marine Ecology Progress Series, 402*, 239-253.

Mantua, N., Johnson, R., Field, J., Lindley, S., Williams, T., Todgham, A., Fangue, N., Jeffres, C., Bell, H., & Cocherell, D. (2021). Mechanisms, impacts, and mitigation for thiamine deficiency and early life stage mortality in California's Central Valley Chinook Salmon. *North Pacific Anadromous Fish Commission, Technical Report, 17*, 92-93.

Martijn, R. L. (2021). *Recreational boating interferes with the behaviour of Atlantic cod (Gadus morhua)* Institute of Marine Research].

McQueen, K., & Marshall, C. T. (2017). Shifts in spawning phenology of cod linked to rising sea temperatures. *ICES Journal of Marine Science, 74*(6), 1561-1573. https://doi.org/10.1093/icesjms/fsx025

Mehrdana, F., Bahlool, Q. Z., Skov, J., Marana, M. H., Sindberg, D., Mundeling, M., Overgaard, B. C., Korbut, R., Strøm, S. B., & Kania, P. W. (2014). Occurrence of zoonotic nematodes Pseudoterranova decipiens, Contracaecum osculatum and Anisakis simplex in cod (Gadus morhua) from the Baltic Sea. *Veterinary Parasitology, 205*(3-4), 581-587.

Moland, E., Synnes, A.-E., Naustvoll, L. J., Freitas, C., Norderhaug, K. M., Thormar, J., Biuw, M., Jorde, P. E., Knutsen, H., & Dahle, G. (2021). Krafttak for kysttorsken-Kunnskap for stedstilpasset gjenoppbygging av bestander, naturtyper og økosystem i Færder-og Ytre Hvaler nasjonalparker. *Rapport fra havforskningen*.

Ogle, D., Doll, J., Wheeler, P., & Dinno, A. (2022). FSA. *Fisheries Stock Analysis. R Package Version 0.9, 3*.

Oomen, R. A. (2019). The genomic basis and spatial scale of variation in thermal responses of Atlantic cod (Gadus morhua). . *Dalhousie University*.

Oomen, R. A., Knutsen, H., Olsen, E. M., Jentoft, S., Stenseth, N. C., & Hutchings, J. A. (2022). Warming accelerates the onset of the molecular stress response and increases mortality of larval Atlantic cod. *Integrative and Comparative Biology, 62*(6), 1784-1801.

Palińska-Żarska, K., Żarski, D., Krejszeff, S., Nowosad, J., Biłas, M., Trejchel, K., & Kucharczyk, D. (2014, 2014/02/01). Dynamics of yolk sac and oil droplet utilization and behavioural aspects of swim bladder inflation in burbot, Lota lota L., larvae during the first days of life, under laboratory conditions. *Aquaculture International, 22*(1), 13-27. https://doi.org/10.1007/s10499-013-9663-4

Pörtner, H. O., & Farrell, A. P. (2008). Physiology and climate change. *Science, 322*(5902), 690-692.

R Develpoment Core Team. (2022). *R: a language and environment for statistical computing* In R Foundation for Statistical Computing. http://www.R-project.org.

Ricker, W. E. (1992). Back-calculation of fish lengths based on proportionality between scale and length increments. *Canadian Journal of Fisheries and Aquatic Sciences, 49*(5), 1018-1026.

Rinde, E., Bekkby, T., Kvile, K. Ø., Andersen, G. S., Brkljacic, M. S., Anglès d'Auriac, M., Christie, H. C., Fredriksen, S., Moy, S. R., & Staalstrøm, A. (2021). Kartlegging av et utvalg marine naturtyper i Oslofjorden. *NIVA-rapport*.

Sandford, M., Castillo, G., & Hung, T. C. (2020). A review of fish identification methods applied on small fish. *Reviews in Aquaculture, 12*(2), 542-554.

Schroeder, D. M., & Love, M. S. (2002). Recreational fishing and marine fish populations in California. *California Cooperative Oceanic Fisheries Investigations Report*, 182-190.

Ski, S. A. (2013). *Demografi, populasjonsstørrelse og vandringer hos atlantisk torsk (Gadus morhua) i indre Oslofjord: en merke-gjenfangststudie* Norwegian University of Life Sciences, Ås].

Sobel, J. (1996). *Gadus morhua. The IUCN Red List of Threatened Species* https://doi.org/https://dx.doi.org/10.2305/IUCN.UK.1996.RLTS.T8784A12931575.en

Stunkard, H. W. (1930). The life history of Cryptocotyle lingua (Creplin), with notes on the physiology of the metacercariae. *Journal of Morphology, 50*(1), 143-191.

Sundby, S., Bjørke, H., Soldal, A., & Olsen, S. (1989). Mortality rates during the early life stages and year class strength of the Arcto-Norwegian cod (Gadus morhua L.). *Rapports et procès-verbaux des Réunions. Conseil permanent international pour l'Exploration de la Mer, 191*, 351-358.

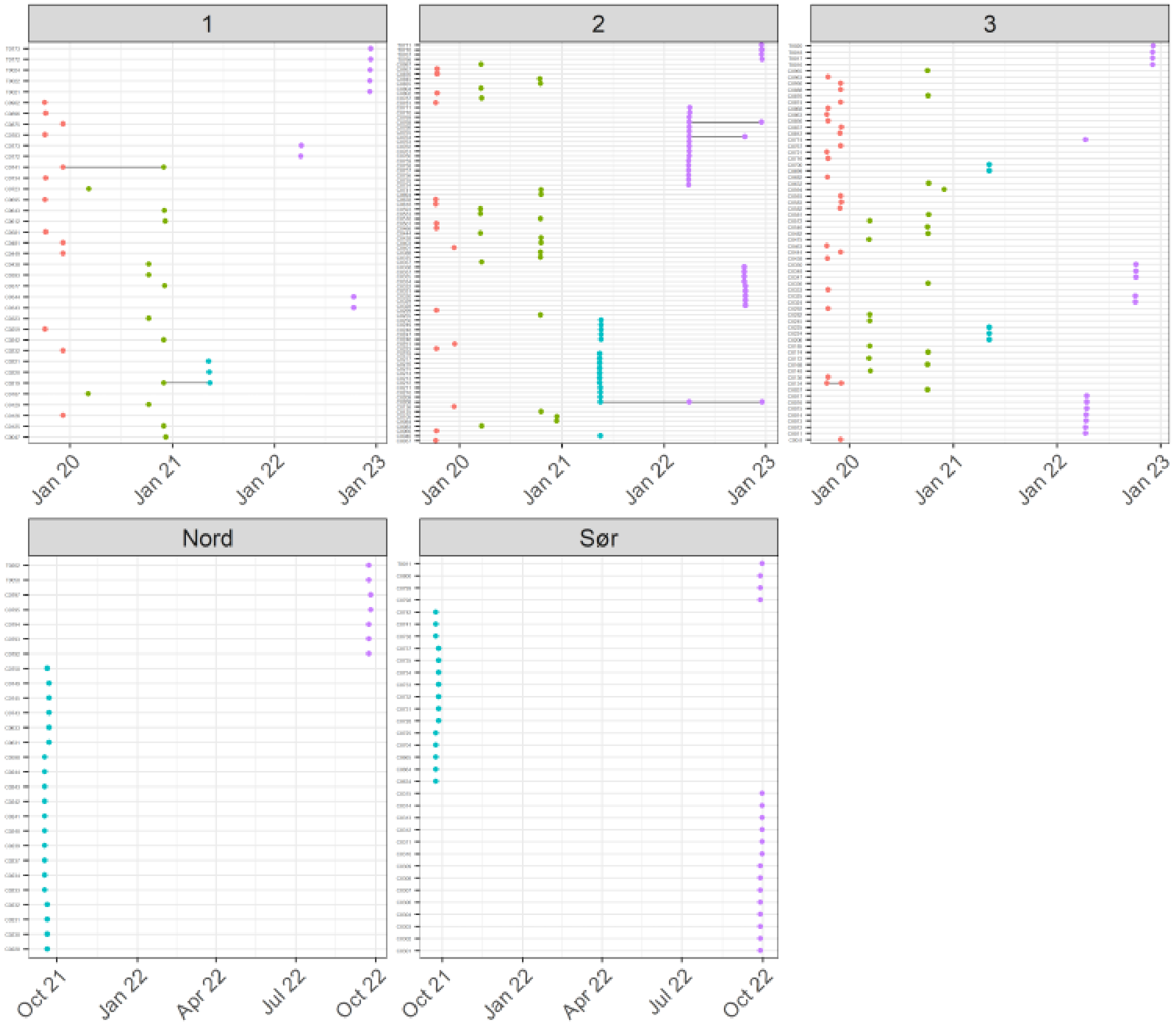
Svåsand, T. (1998). Cod enhancement studies in Norway—background and results with emphasis on releases in the period 1983–1990. *Bulletin of Marine Science, 62*(2), 313-324.

Werner, K. M., Rätz, H.-J., Pedersen, S. A., & Möllmann, C. (2020). Population and abundance dynamics in the offshore stock of Atlantic cod in Greenland waters. *Population dynamics and trophic interactions of Atlantic cod along the Greenland shelf*, 17.

Aalvik, I., Moland, E., Olsen, E., & Stenseth, N. (2015). Spatial ecology of coastal Atlantic cod Gadus morhua associated with parasite load. *Journal of Fish Biology, 87*(2), 449-464.

Aalvik, I. M. (2013). *Life history and spatial ecology of Skagerrak coastal cod (Gadus morhua)*

Appendix



Appendix 1. Timelines for recapturing cod in all three inner fjord zones from January 2020 to December 2022 and the two Drøbak zones from October 2021 to October 2022. Each line represents a unique individual (with tag ID serial number on the Y-axis) and recaptures are bound together by the gray lines. Colors represent the separate years from 2020 to 2022.

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