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Cod on the Dive: Investigating Atlantic Cod of the Inner Oslofjord During Population Decline

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Foreword

Huge thanks to my main supervisor Jonathan Colman for access to his boat, his advice, and his superb knowledge. Equally big thanks to professor Thrond Haugen for his unending patience, and support, and who's knowledge of statistics proved absolutely invaluable.

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Abstract

The Atlantic Cod population of the Inner Oslofjord is in the midst of a collapse and a catch ban has been in effect since 2019. This project was designed to study demography, population size and migration in the Atlantic cod population of the inner Oslofjord, a direct comparison to a similar study in 2011-2012. This would allow me to evaluate the current state of the population and help determine whether the Inner Oslofjord cod fishing ban of 2019 has had any early impact. After nearly two years of field work, using a mark – recapture method where 19-20 fyke nets were used in three zones across the inner Oslofjord to provide randomized and stratified sampling, catches and re-catches were alarmingly low, as was the physical condition of many individuals. 39 out of a total catch of 106 individuals had a condition factor of less than 0.8. The majority of other cod individuals were close to this threshold, and most individuals were below or well below expected weight values (based on Skagerak Cod data). Catch per unit effort (CPUE) decreased by almost 70 % from 2011-2012 to 2019-2020 from 0.23 individuals/trap/day to 0.07 on average. These figures effectively ruled out a study of movement and mortality and instead led me to study the individual age and growth rate, along with total size and health of the population. The decline in both number and physical condition of cod in the inner Oslofjord is alarming. My results across three sampling zones indicate that the pollution and salinity found around the river outlets may not be limiting the growth of cod in the way we would have expected, with no clear trend seen across the gradient. Season effect and bottom type showed significant trends in catch per unit effort (CPUE). Several factors may be involved, with habitat destruction, regime shift, predation, climate change, thiamine deficiency and over-fishing all possible culprits. Further study will be essential in order to fully understand what is happening to this population, and how to protect and improve it.

Introduction

Atlantic cod (Gadus morhua) has been a culturally and commercially important species in Norway for many centuries. Despite this, reports (Lilly et al. 2008) suggest that the Atlantic cod populations around southern Norway have declined considerably over the past few decades. Reasons for this decline have long been debated. Population decline has been attributed to technological advances in commercial fishing (Roessig, J.M. et al. 2004), recreational fishing (Kleiven, A.R. et al. 2016), warmer water due to climate change (Freitas, C. et al. 2015), predation (Hammill et al. 2014), (Barrett et al. 1990), (Cook et al. 2015), changes in habitat (Matsumoto et al. 2020) and unknown population fluctuations (Fromentin et al. 1998).

The Norwegian cod populations can be separated into coastal cod and open ocean, migratory cod. Coastal cod are stationary and tend to be found in shallower water near the seabed whereas the migratory cod, known as Skrei when they migrate into coastal waters for spawning, travel long distances and tend to swim closer to the surface. Due to their different life cycles, it is likely that coastal and migratory cod will be affected in different ways by factors that may lead to a decline in either population. Telemetry studies in 2008 in Vestfjorden/Bærumsbasset (Bærum basin) have shown that the coastal cod in the Oslofjord are very stationary (Ilestad et al 2012, Bøe 2013) making them susceptible to localized factors such as habitat destruction, recreational fishing, or pollution, factors that may all be at play in the inner Oslofjord. Beach seining data from the Institute of Marine Research had shown evidence of fairly good cod recruitment in the years leading up to the previous study in 2011-2012 (Ski, 2013).

Water quality (pollution and salinity) is a factor commonly considered to influence fish populations and was a major consideration when deciding on sampling locations during this study, with zones giving a range of water quality from the deeper, cleaner water along Nesodden to the more dilute, polluted water closest to the mouth of the Sandvikselva. However, my results have shown no clear trend connected to this gradient, therefore will not be discussed in detail. Significant trends were discovered in season effect and bottom type on catch per unit effort (CPUE) and these will be discussed.

While climate change, predation and commercial fishing appear likely culprits in some areas, conditions and the cod populations are sufficiently different inside the inner Oslofjord that, should our findings indicate a declining population, a wide range of other potential factors may need to be considered when investigating this decline. Subpopulations of coastal cod have been found to behave differently and to exhibit different life history patterns (Olsen et al 2004, 2008). This is important in the inner Oslofjord as the sub-populations may be exposed to different factors, and to different magnitudes. These factors may include fishing pressure, pollution, salinity, and others.

Because of this decline and the historically low number of cod and production of fry (Sguotti et al., 2019), a ban on fishing cod in the inner Oslofjord was put in place 15.06.2019. The ban extends from Ellingsvik, just south of Kragerø in Telemark, all the way to the Swedish border (Figure 1). This was intended to aid in the recovery of the disappearing cod stock in the Oslofjord, with The Directorate of Fisheries naming over-fishing, recreational fishing in particular, as the main culprit in the decline along with climate change and environmental impacts from land use. In addition to the total ban in the Oslofjord area, cod fishing was also banned in 14 other areas from Lindesnes to the Swedish border from January 1st to April 30th (Figure 1).

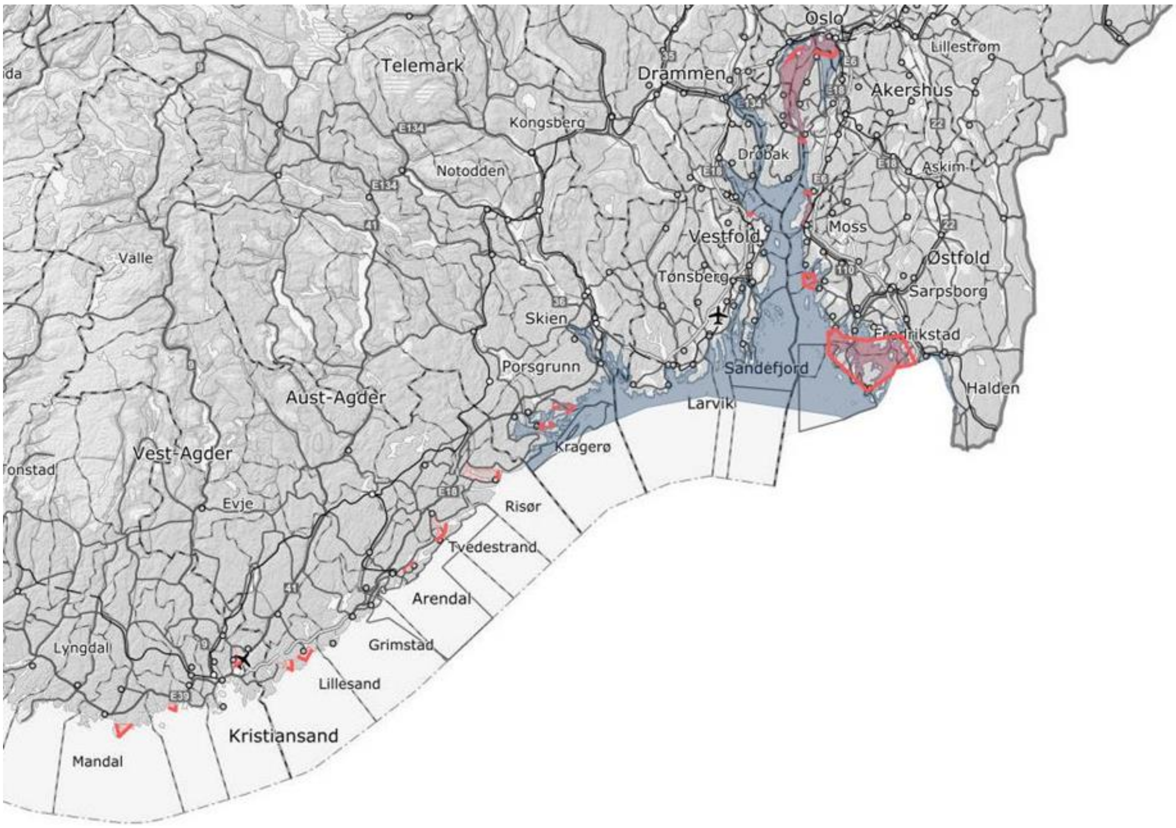


Figure 1. Range of cod fishing ban. Shaded area represents the total ban on cod fishing. Cod fishing is prohibited from Jan. 1 through April 30 in the 14 defined areas along the coast where cod spawn, from Lindesnes to the Swedish border.

map © Fiskeridirektoratet (https://www.fiskeridir.no/Fritidsfiske/Nyheter/2019/Bli-med-aa-redde-torsken)

With climate change and over-exploitation putting global fish populations at an elevated risk of stock collapse, local ecosystems are becoming less resilient to factors such as climate driven recruitment stress. Studies have shown that under similar circumstances to those found in the inner Oslofjord, an area of water separated from the open ocean by a sound and threshold, a fishing ban can allow the cod population to more effectively adapt to environmental change (Lindegren et al. 2010). On this evidence, the ban on cod fishing in the Oslofjord should theoretically make the cod population less vulnerable to climate driven stressors. The results of this study will hopefully shed some light on whether the fishing ban is having a positive impact thus far.

Atlantic cod in the inner Oslofjord are important both commercially and recreationally for hundreds of thousands of anglers (Kleiven, 2016). Recreational fishing is central to the area, with tourist fishing important to the local tourism industry and over 200,000 people 18 years or older fishing at least once in the sea during the year (Kleiven, 2016).

Despite this importance and popularity, very little data exists on the demographics, individual behavior, movement patterns, mortality etc. for Atlantic cod populations in the inner Oslofjord (but see Ilestad et al 2012, Bøe 2013, Ski 2013).

The aim of this project was to investigate cod populations in the inner Oslofjord in order to gain insight into population size, migration patterns, mortality and size distribution using a capture – mark – recapture method. Furthermore, I aimed to compare new data with similar data collected during 2011-2012 (Ski, 2013). Prior to 2011-2012 the only capture – mark – recapture studies conducted in the inner Oslofjord were in 1939 and 1954 by Ruud and Otterbech respectively. These studies showed up to 50-80 % recapture of the marked cod, whereas the 2011-2012 study showed a mere 4.3 % recapture rate with 25 recaptures from 587 marked cod in total. Given the vast difference between these sets of results and coupled with factors such as climate change and pollution from land, an intriguing question is – how will both capture and recapture data differ in the relatively short time period since the last study in 2011-2012 and the data from 1939 and 1954?

Based mostly on anecdotal catch reports from recreational anglers, there appears to be a dramatic change in the Atlantic cod population in the inner Oslofjord over the last five years. However, since the study in 2011-2012 (Ski, 2013) no other data exists on coastal cod in the inner Oslofjord. If this were the case then we would need to ask what factors are causing this dramatic decline and what can be done to help the population recover, with the important first step of the fishing ban already in place. Thus, in order to document and better understand an eventual population decline of this keystone and iconic species and contribute to improvements and optimal management, this study provides insight into the effectiveness of the fishing ban and help influence further decisions on the management of this threatened species. I aim to test both how the population has changed over in the last 10 years, along with how the population is distributed within the inner Oslofjord.

It is believed that water quality may be a major factor limiting the recruitment and development of cod in the inner Oslofjord, with increased pollution from the heavily populated surrounding land and poor water circulation caused by the shallow Drøbak sound and sill. It could be assumed that these conditions will negatively affect the health of cod "inside" this area, i.e., the inner Oslofjord, with negative impacts on development of juvenile cod and physical condition of adult cod.

The location of the three sampling zones in this study (Figure 2) provides contrasting water quality, salinity, depth and bottom type, thus allowing a comparison of how these factors may impact on growth and survival of the cod in the inner Oslofjord. The position of zone 3 (Figure 2), closest to a significant river outlet, leads to the expectation of smaller fish with, perhaps, poorer physical condition. This is due to the more dilute, less saline water and increased amount of pollution in this area due to runoff from the heavily populated area into Sandvikselva. Under the same logic I expected the largest and healthiest catches to be found in the deeper waters to the east in zone 2 along Nesodden (Figure 2). With no major river outlet into this area, I expected conditions to be more optimal for the development of healthy cod. Zone 1, located geographically and assumed to be environmentally "between" zone 2 and 3 (Figure 2), provided gradient for further testing these expectations. I calculate the growth development and body condition of individual cod in each zone to compare these and test this data against key environmental conditions in each zone.

I also test for a seasonal effect in catch numbers and body condition, with physical condition expected to be poorest in spring, right after spawning season and highest in autumn before spawning season has begun. I also expect seasonal variation both due to temperature effects on feeding and due to different motivations (spawning vs feeding). The activity level of the cod will be an important factor, as my method of catch is passive and any factors affecting activity level will influence catchability and be reflected in my CPUE figures.

Materials and Methods

After almost two seasons of field work, the decision was made to shift focus to physical condition, population size and individual size distribution, habitat variables and a comparison between 2011/12 and 2019/2020, as it became clear that our re-capture data would not allow us to analyze migration patterns or mortality. No trend was observed in the gradient along the three sampling zones, but significant trends were discovered in bottom type and season effect on catch per unit effort (CPUE), therefore these are investigated in more detail.

2.1 Study Species

Atlantic cod populations are distributed from all along the North American east coast, the east and west coasts of Greenland, the North Sea, the Baltic Sea and as far north and east as the Barents Sea. Atlantic cod are known to live up to 600 m deep in some areas and have been trawled at up to 460 m deep. Towards the southern limits of their distribution, such as in our study area - the inner Oslofjord, inhabit shallower water (up to the surface and into the tidal zone) in the winter months (personal observation). Individuals and groups have been known to make long migrations – up to 1000 km and have been reported to move up to 5 km in a single day (Ingvaldsen, 2017). Some populations, however, have been known to be relatively stationary. This is believed to be the case regarding the populations in the inner Oslofjord (Ski 2013, Ilestad 2012, Bøe 2013).

The Atlantic cod spawning season is generally between the months of January and April when the water is at its coldest. Eggs can be laid at a wide range of depths from very shallow water to up to 110 m deep. A fully grown adult female Atlantic cod can lay up to nine million eggs in one single spawning season. Despite the millions of eggs laid by each female during a spawning season, only a tiny proportion of these will survive to become fully mature individuals, roughly one egg for every million laid. Hatching of larvae is temperature dependent and can take anything between 10 and 40 days to occur. The larval stage lasts for around 10 weeks where the young cod can increase in size by around forty times while free floating in the water column, drifting with the ocean currents and feeding on plankton. Around May - July the larvae undergo a metamorphosis and become juvenile cod measuring around 3-5cm, then move to the seabed and will measure 14-18 cm in length by the end of their first year. They will reach full maturity somewhere between two and four years of age depending on their stock and have been known to take up to eight years to reach full maturity in the northeast arctic. Atlantic cod can live up to 25 years of age (O'Brien et al. 1993) and are distributed from the east coast of the United States and Canada, throughout the Northern Atlantic and as far east and north as the Baltic Sea and the Arctic (Brander, 2005). Atlantic cod are typically apex predators, but in the presence of a predator will tend to favor rocky terrain for shelter. Juvenile cod will tend to prefer a softer, cobble or gravel substrate that provides some shelter (Gotceitas et al. 1995). The age of all individuals above 30 cm in length was back calculated from scale readings. This allowed me to investigate whether age distribution will be affected by population decline or growth, and poor condition and high mortality.

2.2 Study Area

The study area was the inner Oslofjord. This stretches from Drøbak to Oslo city. My three sampling zones were located towards the northern tip of the Oslofjord (Figure 2). The previous study (2011-2012) included locations at both ends of the inner Oslofjord, Drøbaksundet and Bærumsbassenget (Ski, 2013). This study was centred around Bærumsbassenget as the 2011-12 study did not find any re-catches at Drøbaksundet, and thus, the focus of the study was shifted further inside the inner Oslofjord in 2019 compared to 2011.

Each zone had 19 traps set out in positions distributed evenly along land or in relatively shallow waters (less than 35 m deep).

Zone 1 was located around the south and east of Ostøya (Figure 2). This zone was chosen to provide a direct comparison with the 2011-2012 study, as this exact location was also used in that study. This zone is located in the Bærum basin and measures approximately 0.8 km² in area with a generally flat sand/clay bottom. The traps were laid out in locations that would sample depths both above and below 10m, averaging around 6 m but nothing deeper than the maximum depth in this zone of around 18-20 m.

Zone 2 was located along the west coast of Nesodden in the eastern end of the Bærum basin (Figure 2). This location was selected to investigate both long distance dispersal and different water quality than zones 1 and 3. This zone had a generally thin sand, silt, or gravel bottom. There was a greater range of depths at this location with the traps being set at depths ranging from 5 m – 35 m and the average depth being around 18 m.

Zone 3 was also located in the Bærum basin (Figure 2). This location was chosen to investigate short distance dispersal and also to cover an area with poorer environmental conditions, the anoxic deeper waters of the Bærum basin. This location had a generally silt or sand bottom type and depths very similar to the nearby zone 1, ranging from 3 m-14 m with an average depth of around 7 m.

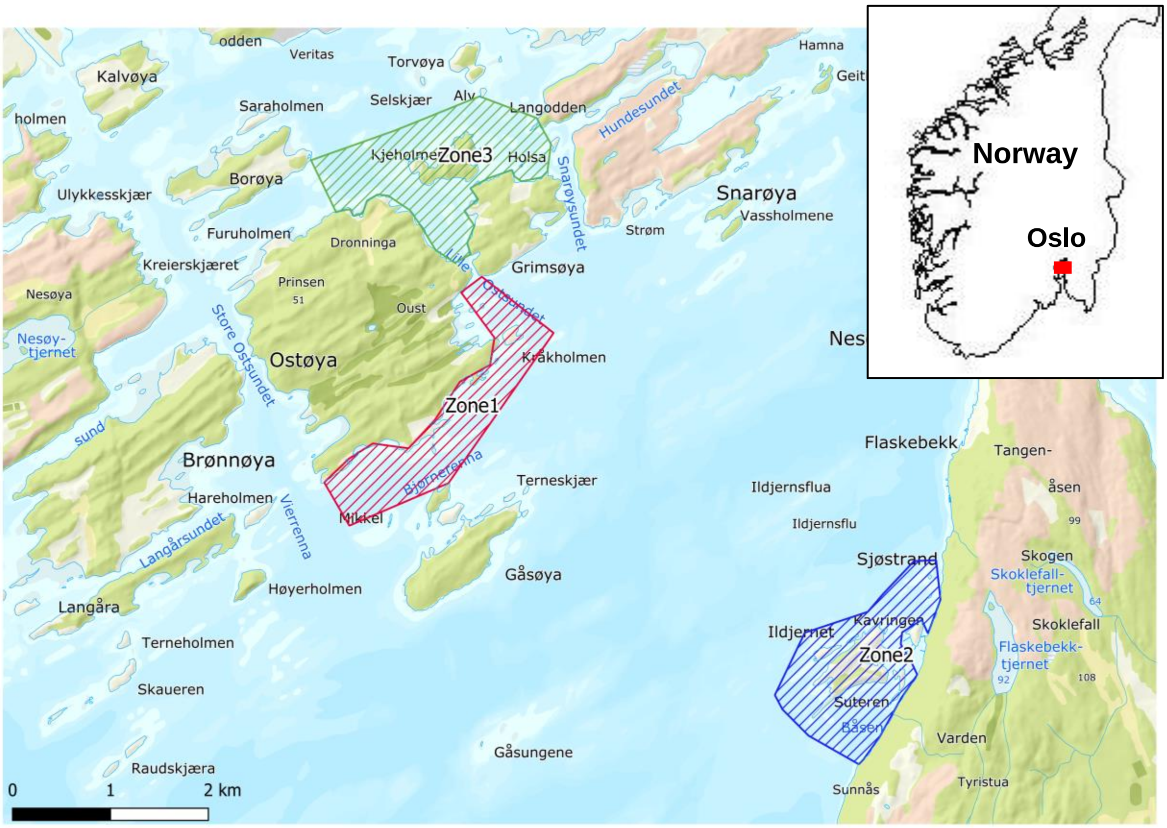


Figure 2. Location of study area in Norway (red rectangle) and distribution of the cod trapping zones (coloured polygons) in the Inner Oslofjord, 2019-2020.

2.3 Data collection methods

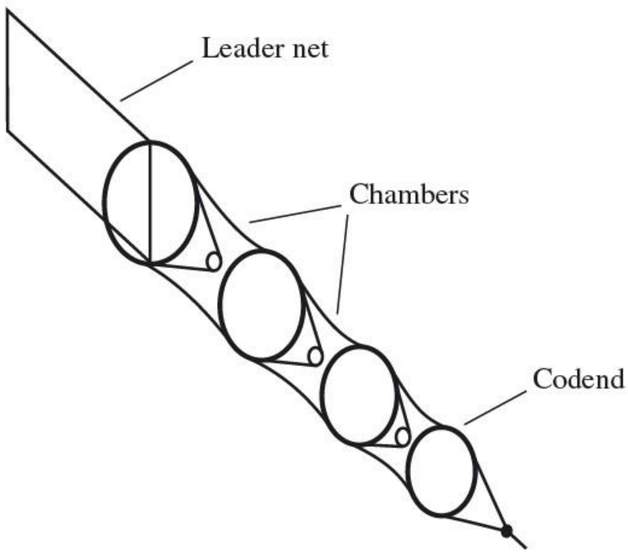
Two seasons of data were obtained in this study in comparison to only one season in the 2011-2012 study. The 2019 season consisted of two sampling periods, the first in late autumn and one in early winter, before the sampling zones had frozen. The 2020 season consisted of three sampling periods, one in early spring followed by two more in autumn and winter, as in 2019. Water temperatures were carefully monitored, and summer months avoided as experience from long-term tagging at the Institute of Marine Research in Flødevigen shows that the survival of tagged cod is significantly lower when the fish are caught at surface temperatures above 16 ° C. High air temperatures also have a large negative effect on the survival of cod (Esben Moland Olsen personal message – Ski (2013)).

Trapping

The previous study in 2011-2012 used several sampling methods (wobbler lures, jig and eel trap) in order to determine whether gear-specific size-selectivity was a factor. The results showed that the eel traps caught essentially all size classes, whereas the other methods were more size selective. Eel traps were chosen and used exclusively in this study. Traps were placed at 19 selected points within each sampling location. These points were distributed as evenly as possible, mostly along land, within each zone. The GPS location of each trap location was logged so that the exact spots could be used in each sampling period. During each sampling period, traps were checked every other day, meaning that every time the traps were checked this would cover an approximate 48-hour period. The process of pulling a trap to the surface was done slowly and carefully to allow pressure equalization of the swim bladder, to avoid barotrauma.

The traps used to catch the cod consisted of a leader net between two sections, each consisting of two chambers and a “Codend” where fish would stay until released (Figure 3).

I began with 20 traps, but one trap was lost in the early days of round 1 in zone 3. From that point on, 19 traps were used.



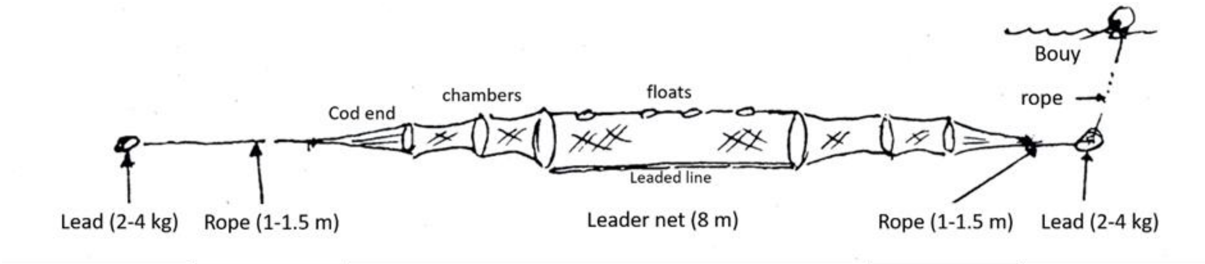


Figure 3. Traps consisting of a leader net, two chambers and a "codend" (Bevacqua et al., 2009)

Tagging and Sampling

Upon entering the boat, the sampling process was carried out as quickly as possible to ensure the wellbeing of the fish. Cod were carefully removed from the trap and placed in a container filled with water to ensure the wellbeing of the fish during the sampling and tagging process. Fish were kept in the container as much as possible throughout the process to minimize air exposure. First, the total length of the cod was measured to the nearest cm. Fish less than 30 cm in length were length-recorded but then returned otherwise unsampled for their own wellbeing. Fish 30 cm or more could be safely tagged and sampled, starting with weight. This was done using a standard hanging scale with the fish placed securely inside a bag for ease of weighing and the bag was wettened to prevent injury to the fish. A Floy tag was then inserted in the flesh just below the dorsal fin, using the spines of the dorsal fin to anchor the tag in place (Figure 4). This was done without anesthetic to avoid excessive handling times. The number of the tag was then logged. Scales (ca. 1-5 items) from the side of the fish just above the lateral line and behind the dorsal fin were gently scratched free with a knife and stored in an envelope. The scales were taken back to the lab for age analysis under a microscope. A small piece of tail or fin was also sampled (a few millimeters and stored in alcohol) to be stored in alcohol for DNA analysis at a later stage (not included in this study). The fish was then returned to the sea and observed to ensure its safe return**.** Any dead fish and those with clear, life threatening damage were euthanized and taken back to the lab for further analysis (for example, stomach content, liver analysis, parasites etc. not included in this study).

Tagging Equipment

Marking equipment was from the company FLOY TAG®. The equipment consisted of a Mark III regular pistol with a heavy-duty needle (Figure 4). The tags were FD-68B T-bar anchor tags labelled with a unique identifier number and a NMBU email address where any tagged fish could be reported if caught by a fisherman not involved with this project.

Figure 4. Tagging equipment: Tagging gun (left) and tag bearing a university email address (right)

Photos: Jonathan Colman.

2.4 Scale Analysis

Growth and age estimation are usually carried out by analysis of bony structures such as scales, otoliths, vertebrae etc. In this study scales were used. Analysis of scales is a non-destructive way of determining the age structure of a fish population, since the scales are taken from live specimens assumed unharming to the sampled individuals. Scales were taken from the medial region of the caudal peduncle, as for many fish species this is where the oldest and non-replacement scales are usually found (Sire & Arnulf, 1990). This approach was used to determine age, cohort assignment and individual growth trajectories. Each of the 106 tagged fish had scale samples taken back to the lab for age analysis. Scale analysis is an important tool in determining the age of a fish. It is known that fish growth rates can differ between populations, species and catchments, with species typically achieving optimal growth in their preferred habitats (Taylor, 2012). It was thus assumed that this could also be used to test growth conditions between the three sampling zones. Fish scales develop rings, known as circuli, as the fish ages. Fish grow faster in the summer and slower in winter, slow winter growth is noticeable by the small spacing between the circuli in this period. This small spacing appears as a dark ring known as an annulus or annuli (plural) (Tzadik et al. 2017). The age of the fish can be determined by counting the number of annuli present on a scale, indicating how many winters the fish has lived through. The distance between each annulus was measured, as well as the full length of the scale. This allowed each year's growth to be compared as a proportion of the full life of the fish, up to the time of sampling. Growth rate can indicate different factors as the fish has grown, such as temperature or feeding.

Of the 106 fish sampled in this study, 84 provided a viable scale sample. 22 samples were unsuitable as the scales samples turned out to be replacement scales, which are unsuitable for reading as they represent incomplete growth patterns, and were therefore unable to be used in an analysis of the age of the fish – this was unavoidable in the field as determination between replacement scales and original scales is almost impossible without the use of a microscope.

Once in the lab, the scales were carefully cleaned to remove any dead skin tissue or other contaminants that would make the reading unclear. Scales were then, one by one, placed in between two glass slides for viewing under a Minox microfiche**.** Once under the microscope, the annuli were carefully counted and marked on a piece of paper (figure number) with the full length of the scale, allowing the size at each age to be back calculated (Figure 4).

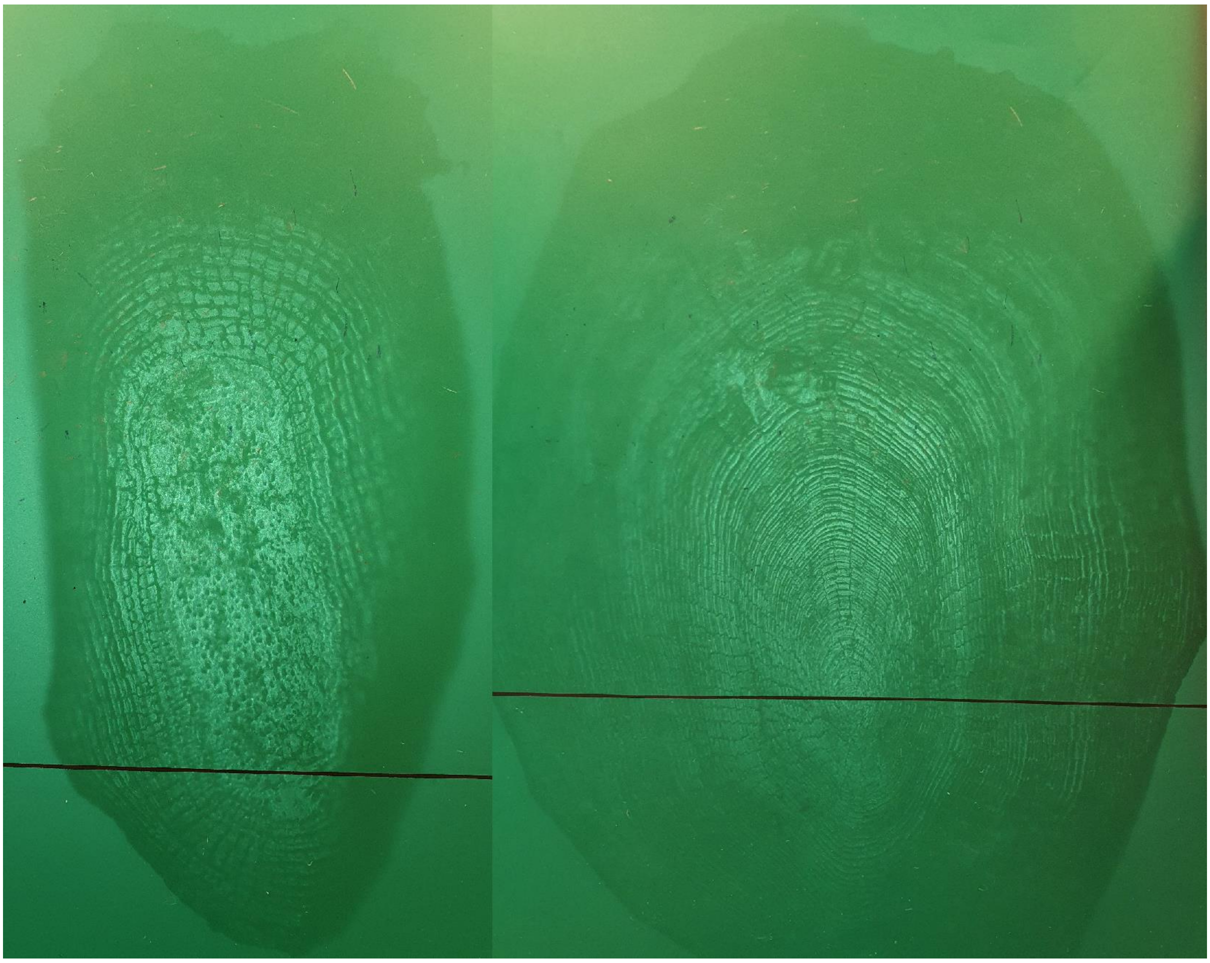


Figure 5. Examples of a typical replacement scale (left) and a regular scale (right) under a microscope. Both scales are from Atlantic cod, but different individuals. The scale on the right is from an 8-year-old cod.

The Fraser-Lee back calculation method was used was used to determine length at age.

The Fraser-Lee equation: $L_t = c + (L_F – c)(S_i / S_r)$

L_t is the length at time *t* (length at age), L_F is the current length of the fish, S_i is the length of the scale at age *i* (age increments on the scale), S_r is the current length of the scale (radius), and c is the correction factor (the length of this fish when the scale was formed.

The Fraser-Lee method is derived from the original method from Fraser (1916) which was adapted by Lee in 1920 to create the current Fraser-Lee method. With this we can use the radius of the scale, the radius of each growth increment of the scale and the length of the fish, to determine the age of the fish when caught and the length of the fish at each year of its life. A von Bertalanffy growth model will be used to plot the zone specific length at age from these scale readings.

Lee's Phenomenon

When back-calculating the age of a fish, it is possible that older fish will show slower growth rates than younger fish. Lee's phenomenon occurs when fish populations with slower growing individuals suffer less mortality when young. The results will then be skewed towards the slower growing fish, as the faster growing fish died at a young age. Reasons for this phenomenon can vary. I will test for this effect in my results (Ricker, 1992), (Lee, 1912).

2.5 Condition Weight-length relationship and *k*-factor

To determine the physical condition of the fish caught during this study measurements of length (L, cm) and weight (W, g) were used. This was done following two approaches: Fulton's *k*-factor (Ricker, 1992) and comparison with expected length-specific weight from the Skagerrak region. Fulton's *k*-factor was estimated as: $k=W/L^3*1000$, and expected weight (Wexp) was estimated from: $Wexp=0.0055L3.171$. I will use a scoring system to describe the body condition (below 0.8 = poor condition) (Mello and Rose, 2005).

2.6 Bottom Type

In order to explore habitat effects on CPUE, I assigned bottom / sediment type for each trap location using the trap coordinates recorded when the traps were first set to match with bottom type using maps downloaded from kart.kystverket.no. These same GPS waypoints were used during every subsequent trapping period.

Across the three zones 8 different bottom types were identified (Figure 6).

1. Thin or incoherent sediment over bedrock
2. Silt
3. Mud
4. Gravel
5. Gravelly, sandy mud
6. Muddy, sandy gravel
7. Gravelly, muddy sand
8. Gravel/stone/boulder

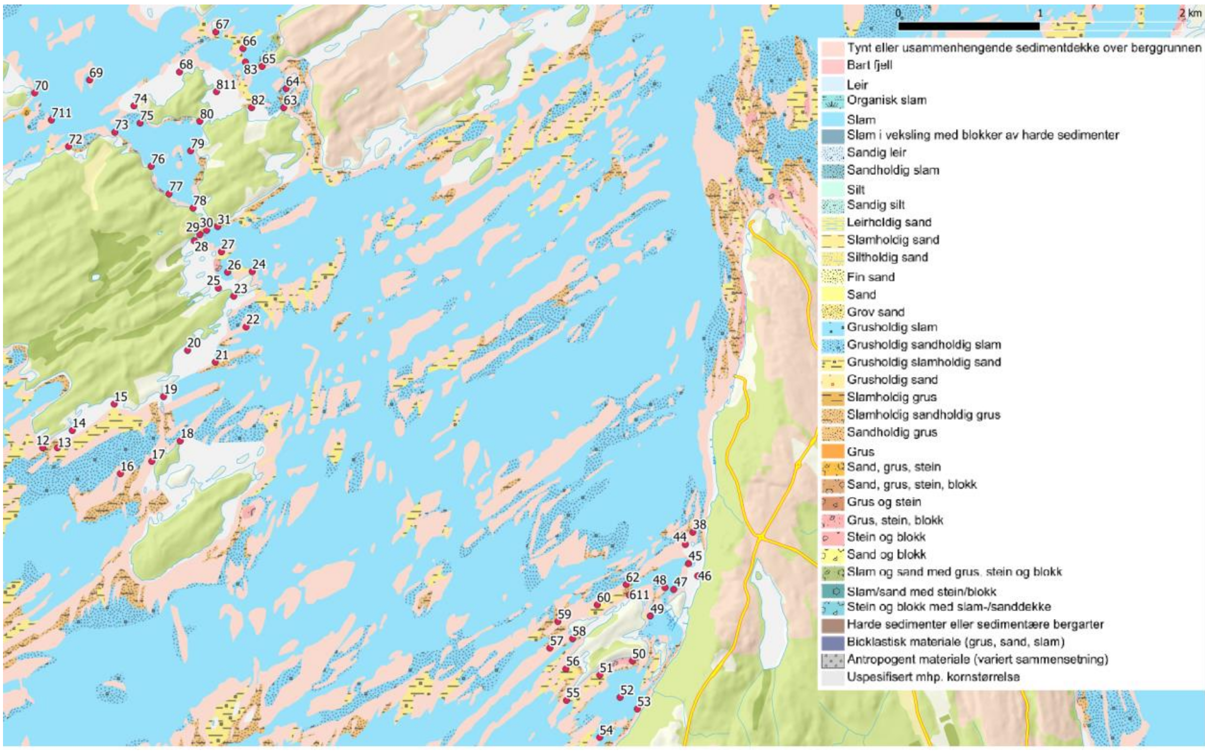


Figure 6. Bottom type for each GPS waypoint. Bottom type info obtained from kart.kystverket.no.

These 8 bottom types were organized into three categories for more effective analysis (numbers reflect item number in the just mentioned bottom type list).

- Soft (2, 3, 5, 7)
- Hard (1, 8)
- Gravel (4, 6)

2.7 AIC Model Selection

Akaike Information Criterion (AIC) gives an estimate of model suitability by using the trade-off between the quality of fit and model parsimony. Model parsimony is important because AIC penalises by a factor of 2 for each variable added. A parsimonious model should have just the right number of variables needed to explain the model well (Bozdogan, 2000), (Anderson et al., 2008).

AIC model selection was used to determine the most suitable model to compare catch per unit effort (CPUE) with the variables, round (including season), zone, depth, and bottom type. This was carried out using R.

3 Results

3.1 Catch per Unit Effort (CPUE)

CPUE was highest in autumn, followed by winter and spring. Winter 2020 was poorer than winter 2019. Spring 2020 numbers were low, but the previous spring was untested therefore no direct comparison available. Overall, 2020 figures were lower than 2019 (Figure 7).

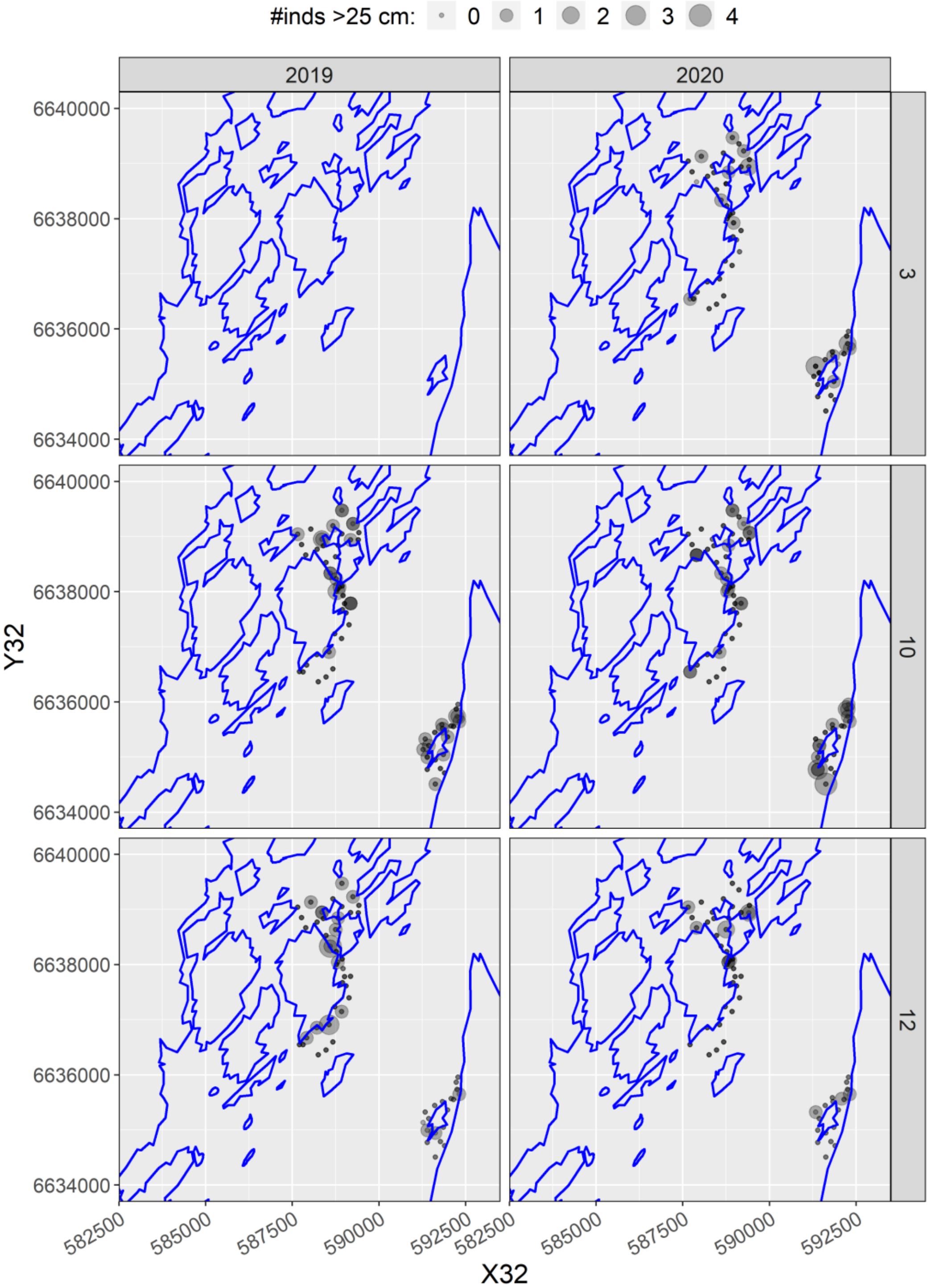


Figure 7. Bubble plot showing CPUE by location.

A comparison of 2011-2012 and 2019-2020 showed a significant decrease in catch per unit effort in less than 10 years from overall mean (±SD) CPUE at 0.23±0.20 to 0.07±0.05 inds/trap/day, i.e., a 69.6 % decrease (one-way anova: $F_{1,70}$=28.351.16, p<0.0001; Figure 8).

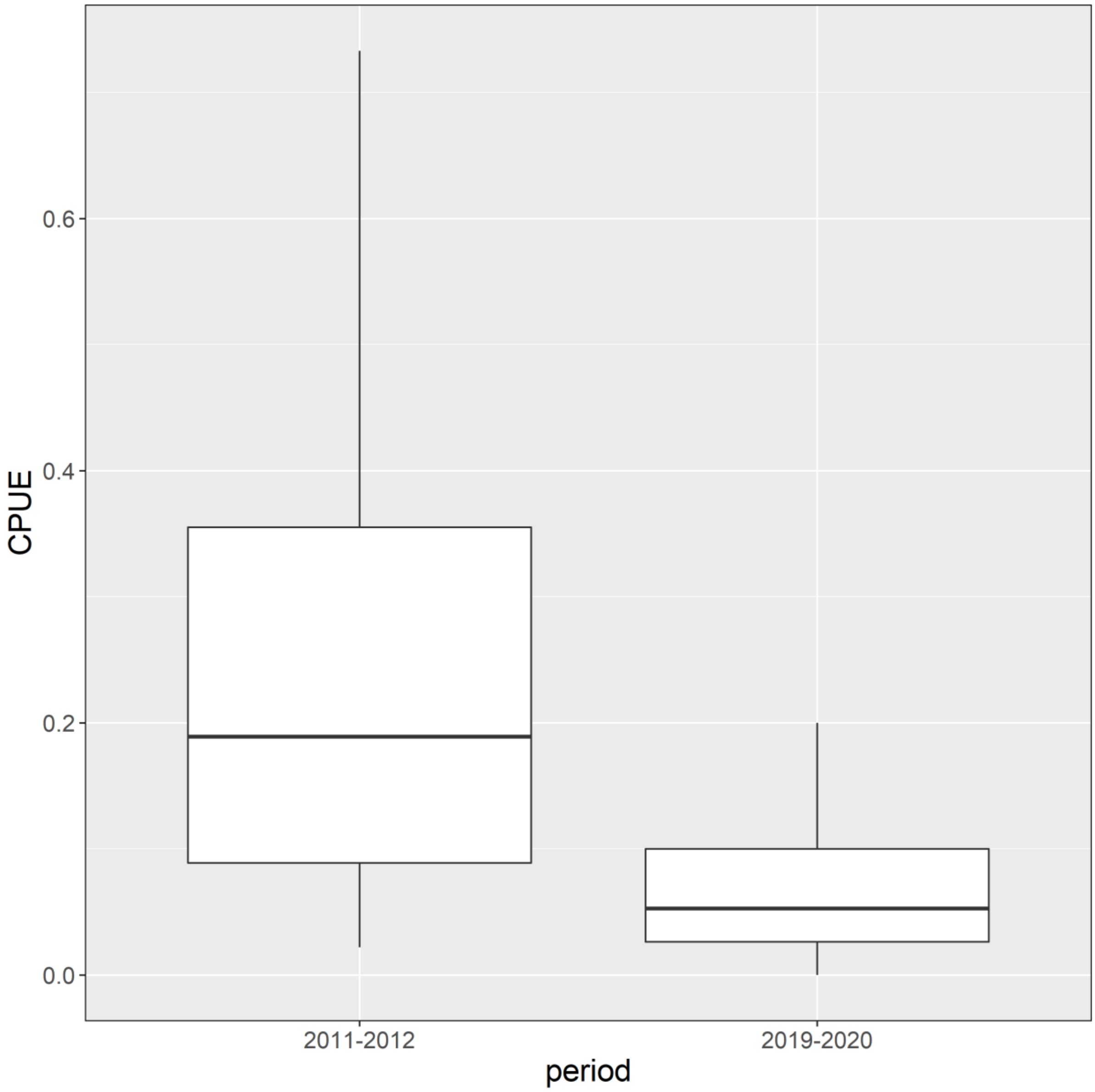


Figure 8. Boxplot comparing catch per unit effort (CPUE, # inds/trap/day) from this study (2019-2010) and the previous study (2011-2012).

In the 2011-2012 study, autumn CPUE had a much higher maximum (0.75 # inds/trap/day) than spring or winter but with the majority of values grouped between the mid (0.3) and lower end of the scale (0.095) (Figure 9). The winter season had a much lower maximum (0.46) and slightly lower minimum (0.08) with a fairly even spread of values over this scale. Spring season followed a similar pattern to autumn but with a significantly lower maximum (0.55) and a lower minimum (0.02). 2019-2020 CPUE values did not exceed 0.2 for any season. Autumn values were again the highest, with most values grouped around the mean of 0.1 with max 0.2 and min 0.0. Winter had similar max and min values of 0.19 and 0.0 but most values were grouped around the minimum. Spring values were low, with values spread evenly between a maximum and minimum of 0.1 and 0.0.

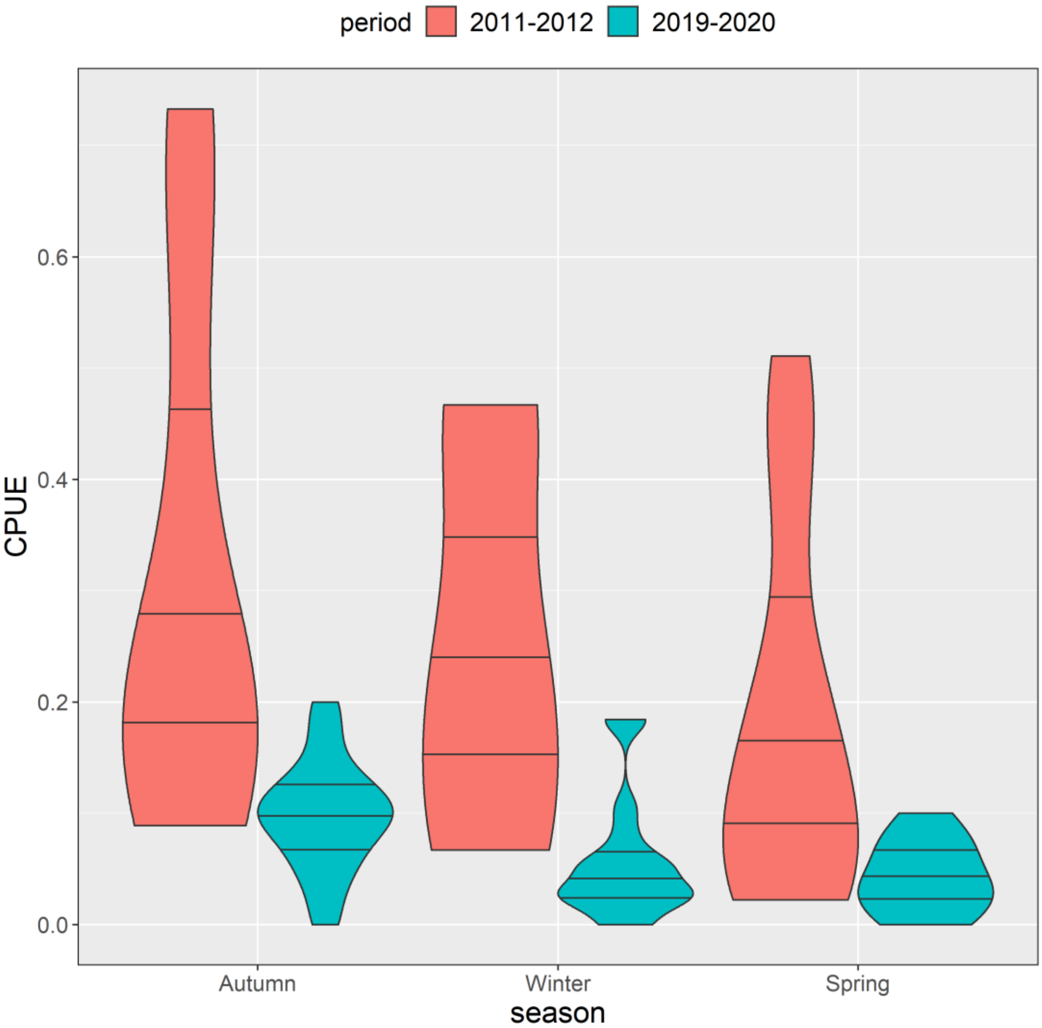


Figure 9. Violin plot of catch per unit effort (CPUE, inds/trap/day) by season for this study (2019-2020) and the previous study (2011-2012, Ski (2012)). Violin widths display the

releative frequency and the three horizontal lines within the violins represent 25, 50 and 75 percentiles.

3.2 Correlates of CPUE

The model selection among candidate models fitted to CPUE yielded a model with round + bottom type as the one with most support in the data (Table 4). This model attained 42.5 % of the AICc-support and predicted CPUE to be significantly higher on a soft bottom, followed by hard bottom and gravel (Table 5, Figure 16). The season effect was related to a much higher CPUE in autumn compared to compared to spring and winter (Table 5, Figure 16) The second-most supported model attained 16.6 % of the AICc-support (ΔAICc=1.88) and modelled CPUE as function of round+Zone. This candidate model predicted zone 1 to have the lowest CPUE and zone 2 and 3 to have CPUEs that were 0.036 and 0.038 inds/trap/day higher, respectively.

Table 1. Model selection metrics for candidate models fitted to explain variation in CPUE for cod from inner Oslofjord caught during 2019-2020. BottomType included 9 sediment/bottom type categories that were merged into three categories (soft, gravel and hard) for the BottomTypeSimp effect. K=number of parameters; AICc = corrected AIC; ΔAICc=difference in AICc compared to lowest AICc; ModelLik=Model likelihood; AICcWt= relative AICc support, LL=loglikelihood.

Model	K	AICc	AICc	ModelLik	AICcWt	LL
round+BottomTypeSimp	8	-142.145	0.000	1.000	0.425	81.130
round+Zone	8	-140.266	1.879	0.391	0.166	80.190
round+Zone+depth²	10	-139.693	2.453	0.293	0.125	83.180
BottomTypeSimp	4	-138.812	3.334	0.189	0.080	73.919
round	6	-138.166	3.979	0.137	0.058	76.218
Zone	4	-138.039	4.106	0.128	0.055	73.533
BottomType	8	-137.860	4.285	0.117	0.050	78.987
round+Zone*depth	11	-137.158	4.987	0.083	0.035	83.704
round+BottomType	12	-132.827	9.318	0.009	0.004	83.446
round*depth	11	-131.159	10.987	0.004	0.002	80.704
round*BottomTypeSimp	14	-123.915	18.230	0.000	0.000	83.199
round*depth²	14	-123.355	18.790	0.000	0.000	82.919
round*BottomType	15	-121.740	20.405	0.000	0.000	84.442
round*Zone	16	-117.035	25.110	0.000	0.000	84.592

Table 2. Parameter estimates of the selected CPUE model (Table 1) and the corresponding test statistics of the model Anova. The bottom type included in this model corresponds to BottomTypeSimp in Table 1. Model Fit statistics: F=3.811, df= 6/37, p=0.005, R^2=0.382. Terms: winter 2019, autumn 2020, winter 2020, spring 2020, intercept = autumn 2019. Soft bottom type = sand/silt/mud, hard bottom type = bedrock/stone/boulder.

Parameter estimates				Test statistics					
Term	Estimate	SE		Effect	DF	SS	MSS	F-value	p
Intercept	0.072	0.015		round	4	0.02372	0.00593	3.4028	0.01818
roundWi19	-0.031	0.023		Bottom Type	2	0.016129	0.0080644	4.6276	0.01608
roundAu20	0.005	0.021							
roundWi20	-0.051	0.021							
roundSp20	-0.050	0.020							
BottomType[Soft]	0.046	0.016							
BottomType[Hard]	0.016	0.018							

A very clear pattern was evident when CPUE was modelled with the variables bottom type and round. Catches were highest in the autumn rounds, with both autumn rounds (2019 and 2020) showing very similar CPUE values (max around 0.17). Spring and winter 2020 had very similarly low values to each other (max 0.11). Winter 2019 experienced higher CPUE than spring and winter 2020 but still significantly lower than autumn CPUE.

The soft bottom type - predominantly consisting of silt, mud and sand produced clearly the highest CPUE in every round with almost double the value of the gravel bottom in most cases. The hard bottom type in each round produced lower CPUE than the soft bottom and higher than, although closer to, gravel.

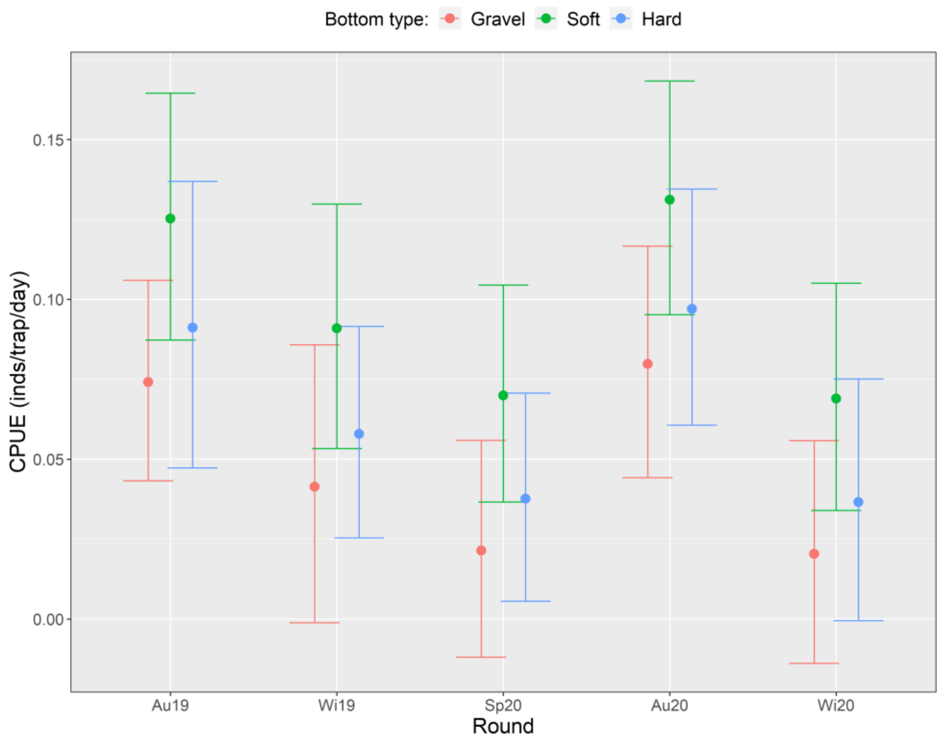


Figure 10. Prediction plot of the selected catch per unit effort (CPUE) model (Table 1 and Table 2) by round and bottom type. Horizontal lines are error bars representing the 95 % confidence interval. X-axis abbreviations mean autumn and winter of 2019, and spring, autumn and winter 2020.

3.3 Length-weight relationship

Condition factor was alarmingly low, with 39 individuals (37%) in a physical condition described as poor (k-factor below 0.8), and the majority of the rest close to this limit (Table 3, Figure 11). Mean body condition was highest in zone 2 (0.882), followed by zones 3 (0.828) and 1 (0.756).

Table 3. Average length, weight and condition factor of cod caught in each zone and period. Figures in brackets represent values if cod under 30 cm length were included, however if these fish were immediately returned after length measurement no weight was measured, or condition factor calculated.

Zone	Period	No. of Inds	Length	Weight	SD	Condition Factor	SD
1	Autumn 19	7	51.57	1235.71	588.7	0.85	0.034
1	Winter 19	6 (10)	55.17 (40.8)	1608.33	705.2	0.92	0.206
1	Spring 20	2 (3)	55.5 (43.67)	1620	777.8	0.94	0.219
1	Autumn 20	4	46.25	515	409.8	0.48	0.240
1	Winter 20	8 (12)	49.88 (39.96)	973.75	821.8	0.59	0.157
2	Autumn 19	12 (17)	44.78 (37.76)	956.67	433.3	1.01	0.159
2	Winter 19	3 (10)	46 (26.6)	946.67	433.2	0.93	0.181
2	Spring 20	8 (16)	55.53 (39.75)	1881.25	847.3	1.04	0.178
2	Autumn 20	11	43.91	721.82	546.4	0.73	0.120
2	Winter 20	2 (4)	42 (30.63)	530	169.7	0.7	0.014
3	Autumn 19	13 (16)	57.85 (49.33)	1798.46	788.9	0.88	0.150
3	Winter 19	11 (16)	55.55 (44.78)	1443.45	394.4	0.83	0.090
3	Spring 20	7 (9)	57.07 (49.39)	1907.14	963.5	0.95	0.110
3	Autumn 20	10	53.4	1159	877.3	0.61	0.245
3	Winter 20	1 (3)	53 (30)	1300	N/A	0.87	N/A

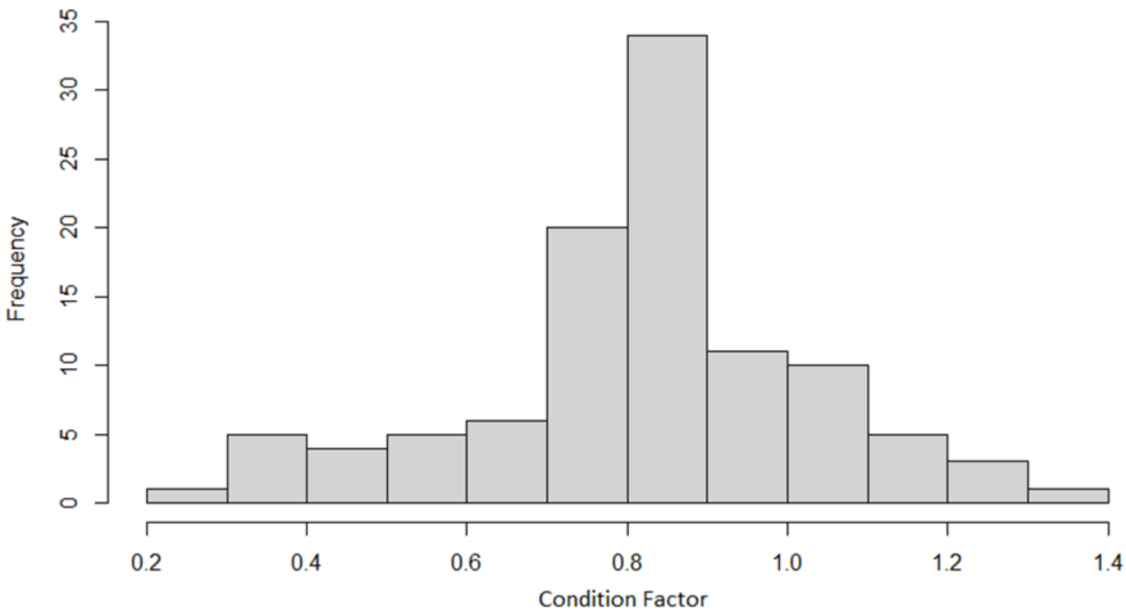


Figure 11. Histogram of >30 cm cod condition factors from inner Oslofjord during 2019-2020.

Data on expected weight for Atlantic cod was based on Skagerak coast data (as reported on www.fishbase.de). Our data from all catches of cod individuals above 30 cm in length showed relatively few fish at or above expected weight (Figure 12). The vast majority were below (91 individuals), with many well below expected weight. When analyzed by year, the results show an alarming decrease in size-adjusted weight in the 2020 catches compared to those from 2019

(Figure 12) and the *k*-factor was on average significantly lower in 2020 (mean±SD: 0.75±0.15) than in 2019 (0.90±0.24) (one-way ANOVA: $F_{1,103}$=14.29; p=0.0003).

Mean condition factor across the three zones showed individuals from zone 2 to have the best body condition (K factor 0.882) followed by zone 3 (0.828) and zone 1 (0.756).

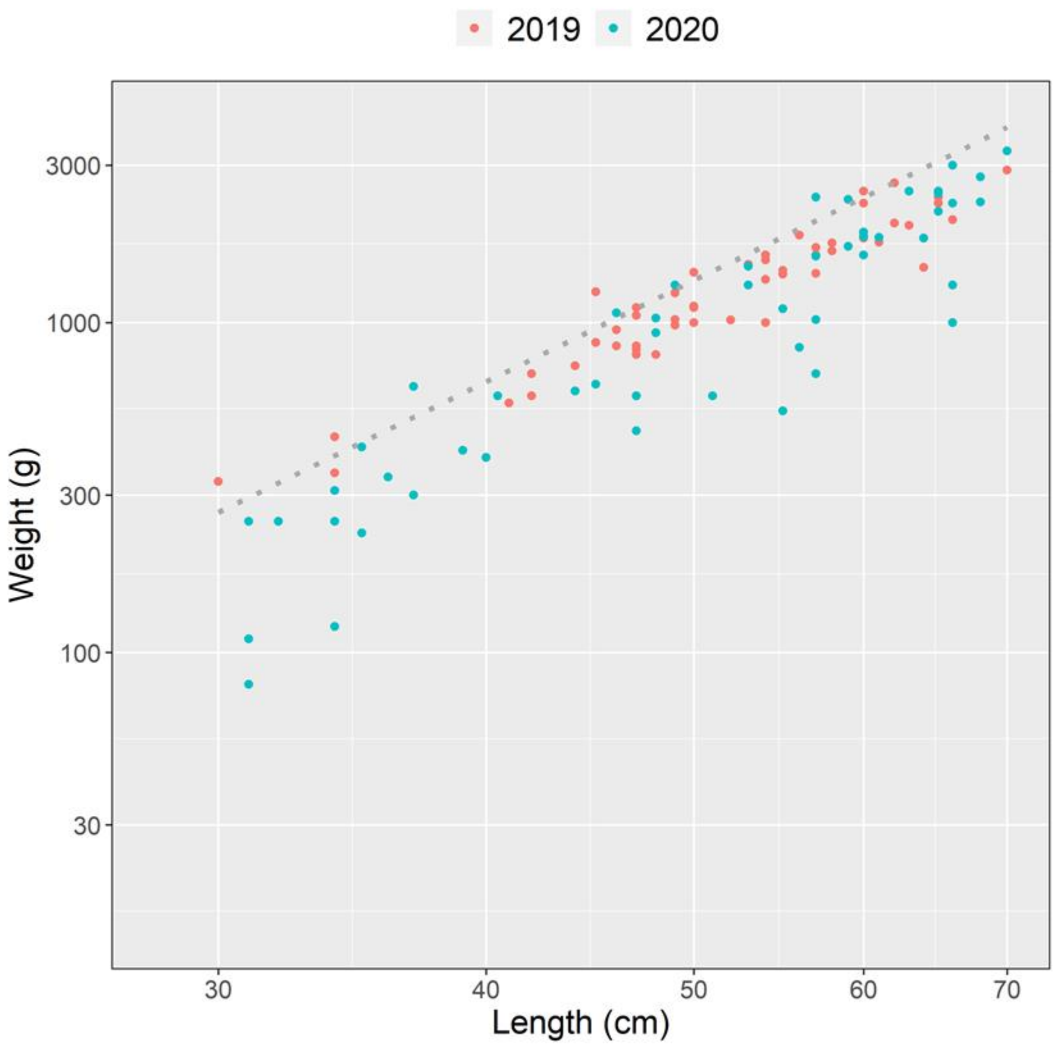


Figure 12. Length (cm) and weight (g) of all cod catches over 30 cm during 2019 and 2020 compared with expected weight (grey dotted line) data obtained from www.fishbase.de by year.

The model selection among candidate models fitted to body weight data yielded a model with ln(length)+year+season+Zone as the one with most support in the data (Table 2). This model predicted length-specific weight to be larger in 2019 than in 2020 and largest in zone 2, followed by zone 3 and 1 (Table 2, Figure 13). The month effect was related to a much higher length-specific weight in March (month=3) compared to November and December (Table 2, Figure 13).

Table 3. Model selection metrics for candidate models fitted to explain variation in ln(weight) for cod from inner Oslofjord caught during 2019-2020. K=number of parameters; AICc = corrected AIC; ΔAICc=difference in AICc compared to lowest AICc; ModelLik=Model likelihood; AICcWt= relative AICc support, LL=loglikelihood.

Model	K	AICc	ΔAICc	ModelLik	AICcWt	LL
ln(length)+year+month+Zone	8	-0.864	0.000	1.000	0.439	9.182
ln(length)*month+year+Zone	10	-0.036	0.827	0.661	0.291	11.188
ln(length)*year+month+Zone	9	0.889	1.753	0.416	0.183	9.503
ln(length)*year*month+Zone	13	2.370	3.233	0.199	0.087	13.815
ln(length)+Zone+year	6	29.010	29.874	0.000	0.000	-8.077
ln(length)*year+Zone	7	29.140	30.003	0.000	0.000	-6.993
ln(length)*Zone+year	8	32.028	32.891	0.000	0.000	-7.264
ln(length)*Zone*year	13	36.823	37.687	0.000	0.000	-3.411
ln(length)	3	54.040	54.903	0.000	0.000	-23.901
Intercept	2	247.161	248.025	0.000	0.000	-121.522

Table 3. Parameter estimates and corresponding test statistics for the selected candidate model fitted to ln(weight) data (Table 3). SS=sum of squares; MSS=mean sum of squares. Model fit statistics: $F_{6,98}$=180.6; p<0.0001; R^2=0.912.

Parameter estimates			Test statistics					
Term	Estimate	SE	Effect	DF	SS	MSS	F-value	p
Intercept	-4.543	0.470	ln(length)	1	52.534	52.534	997.490	<0.0001
ln(length)	3.046	0.112	Year	1	1.284	1.284	24.378	<0.0001
Year[2020]	-0.383	0.051	Month	2	2.564	1.282	24.3459	<0.0001
Month[Nov]	-0.444	0.073	Zone	2	0.683	0.341	6.4818	0.0023
Month[Dec]	-0.426	0.082						
Zone[2]	0.206	0.063						
Zone[3]	0.037	0.059						

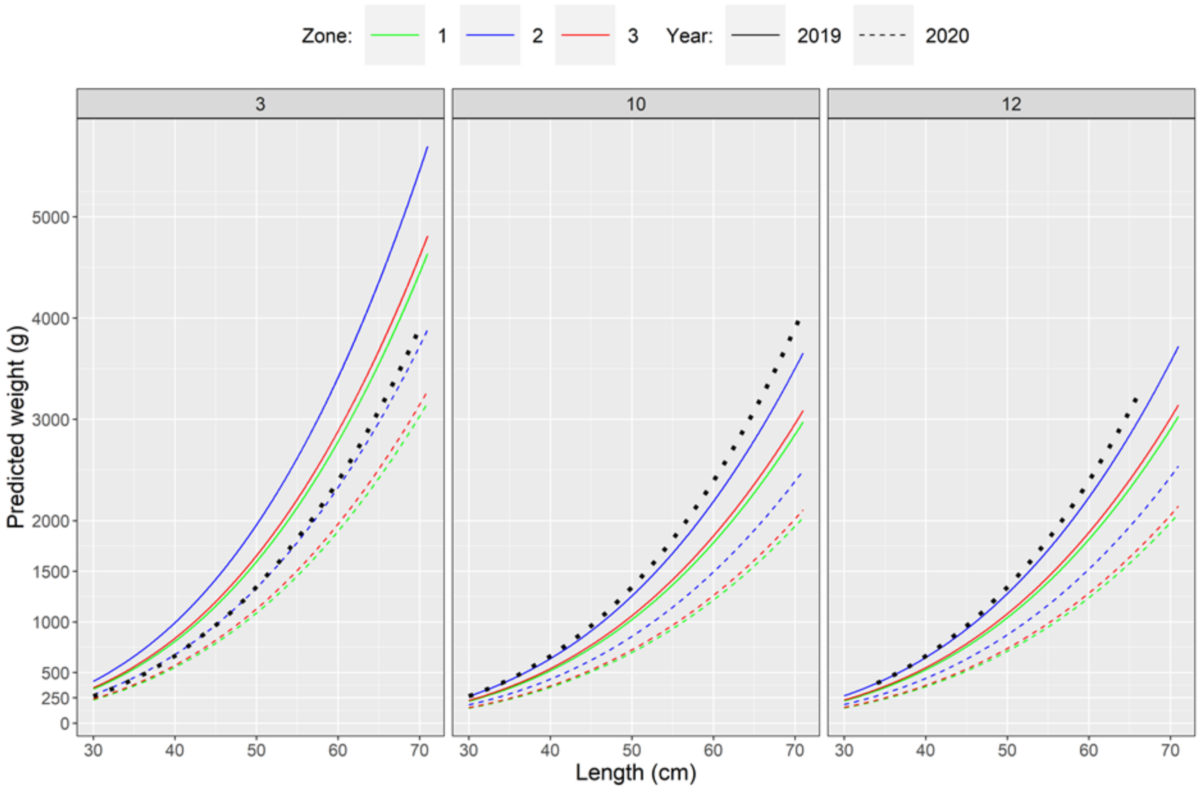


Figure 13. Predicted body weights of cod from inner Oslofjord as function of year, month number (panel headers) and sampling zone. Predictions were made from the selected model provided in Table 3 and Table 4. Dotted black line represents the length-adjusted expected weight for Skagerrak cod (from www.fishbase.de).

3.4 Age and length back-calculation from Scale Readings

In total, 84 of 102 fish provided a viable scale sample, with 22 proving unreadable due to them only providing replacement scales. The age of the fish in this study ranged from 1 to 8 years with the mean age being 3.4 years, zone 2 had the lowest mean age (2.96 years) and zone 3 the highest (3.74 years), while zone 1 has a mean age of 3.32 years. The scale readings revealed strongest cohorts from 2015, 2016 and 2017, 2016 in particular, with numbers tailing off in the previous and later years. Zone 1 had individuals from 5 cohorts only, whereas zones 2 and 3 had 7 and 8 cohorts, respectively (Figure 14). Figure 15 (boxplot) showed that fish in zone 3 had lived longer than those in zones 1 and 2, with a maximum age of 8 years compared to 6 years in the other zones. While zone 1 had a maximum age of 6 years, very few individuals were found to be over 4 years old. The fitted zone-specific von Bertalanffy growth functions showed that length was largest in zone 1, and the nearby zone 3 similar though slightly lower (Table 4). Zone 2 had significantly lower length than zones 1 and 3.

A von Bertalanffy prediction plot indicated that zone 3 has the fish with the biggest length at age. The length at age of fish from zone 1 was similar but slightly lower than zone 3. No fish older than 6 years were found in zones 1 or 2, in fact only a handful of individuals older than 4 years were caught in zone 1. Fish from zone 2 had by far the lowest length at age of the three zones. Back-calculated length data showed first year growth (L1) to range from 7.4 to 25.6 cm (mean 14.6 cm).

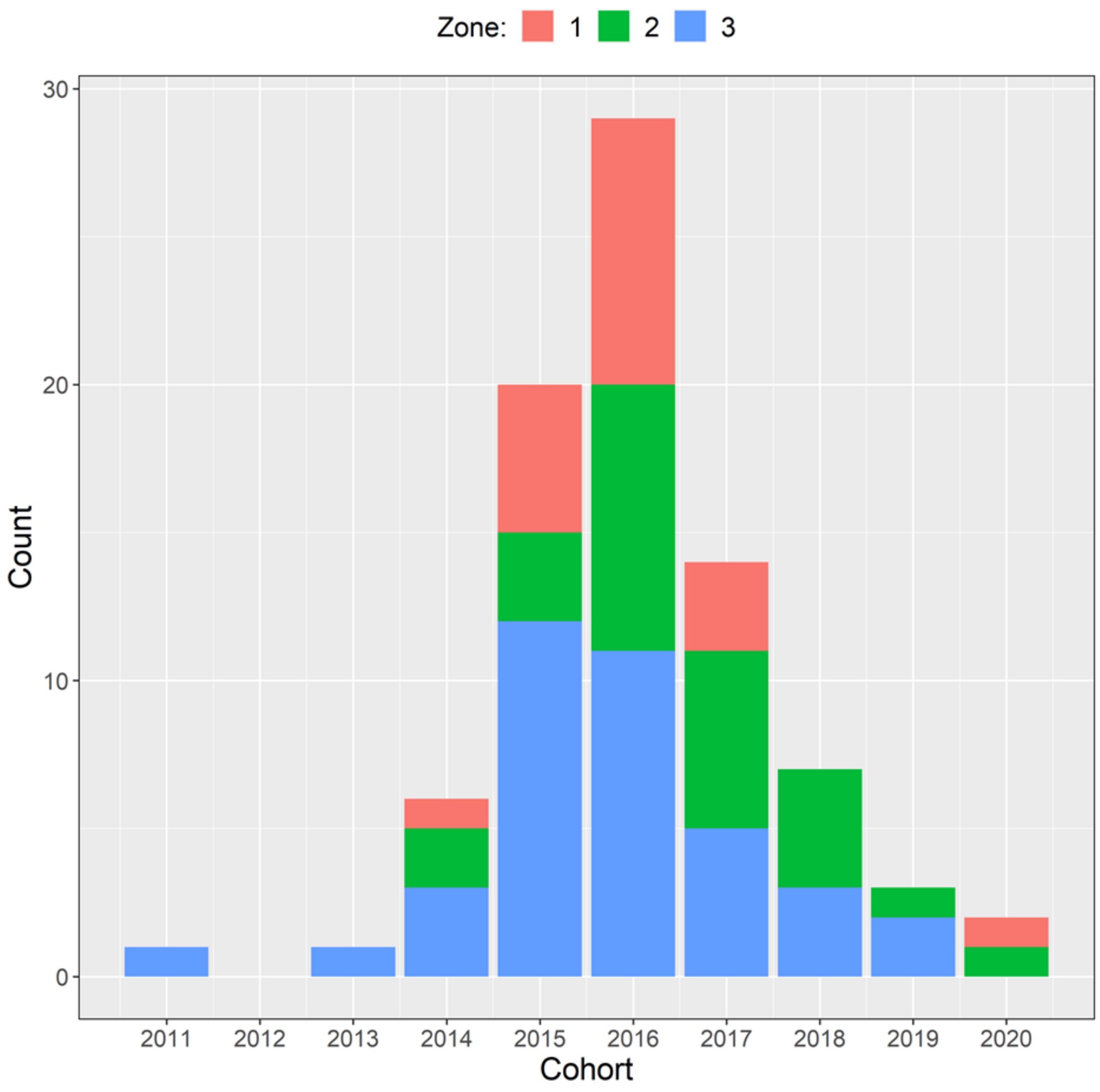


Figure 14. Zone-specific number of individuals per cohort for cod caught in the inner Oslofjord during 2019-2020 as revealed from scale readings.

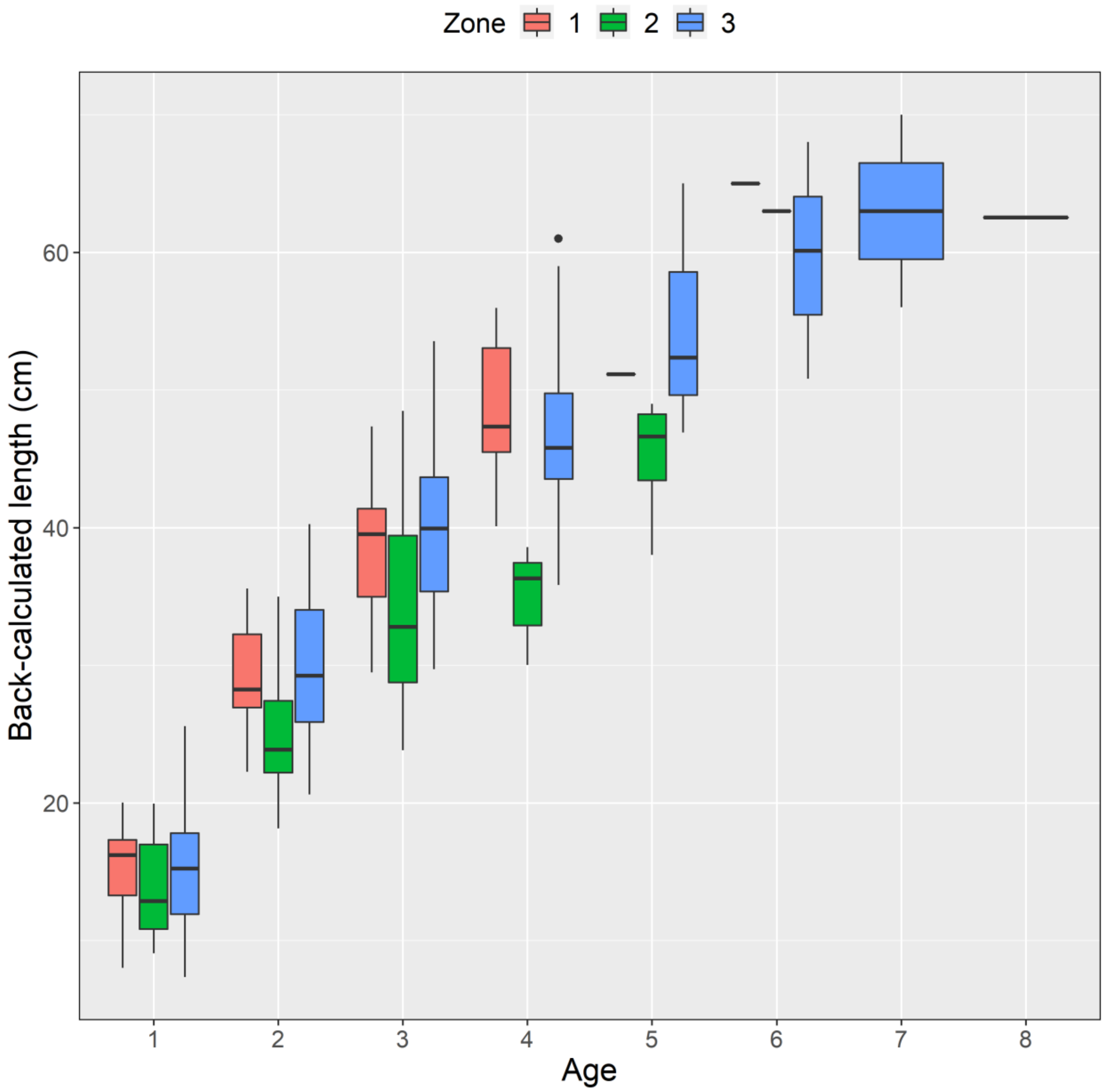


Figure 15. Boxplot of back calculated length with age and zone. The horizontal black lines represent the 50th percentile. The top and bottom of the boxes represent the 25th and 75th percentiles. The vertical lines are error bars representing the 95 % confidence interval. Outliers are shown as circles.

There was no support in the back-calculation data for a Lee's effect as revealed from a linear regression between back-calculated first-winter length and age-at-catch (linear regression: slope= -0.207± 0.345(SE), p=0.55).

Table 4. von Bertalanffy parameter estimates for cod caught in three sampling zones in inner Oslofjord during 2019-2020.

	Linf		K		t0	
	Est	SE	Est	SE	Est	SE
Zone 1	88.177	19.440	0.201	0.073	0.043	0.170
Zone 2	79.102	25.909	0.171	0.089	-0.152	0.263
Zone 3	73.672	6.211	0.264	0.045	0.093	0.114

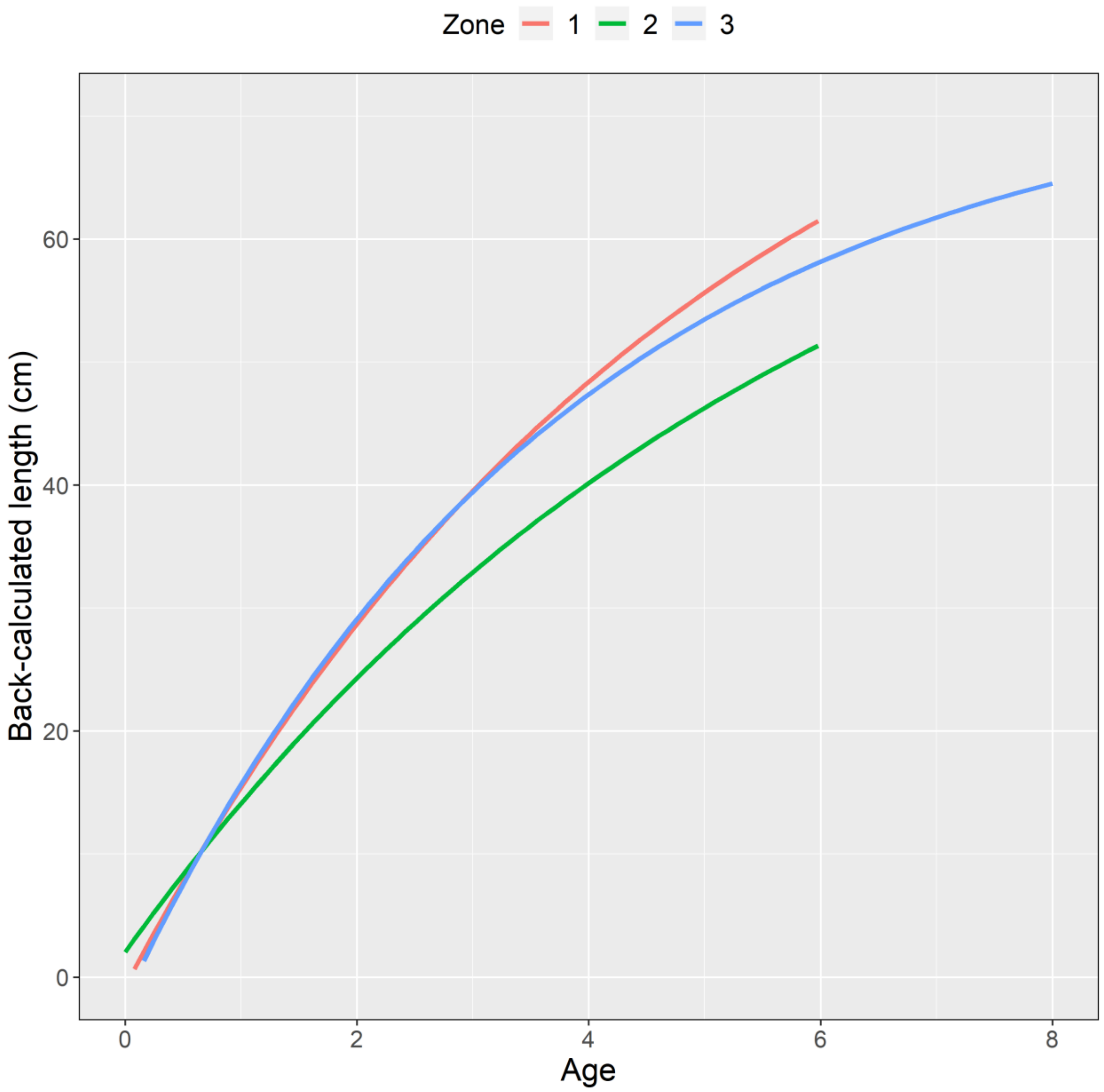


Figure 16. Predicted von Bertallanffy growth trajectories as function of zone.

Discussion

As a direct comparison to the previous study in 2011-2012, the results of this study are alarming. In 2011-2012 a total of 578 cod were caught (293 in traps) and tagged in a single season. This number was considered a little low for good estimates but did allow for estimates of population size, as well as analysis of movement and mortality. This time, a total of 106 cod caught including just two recaptures in almost 2 full seasons (fall and winter 2019 and spring, fall and winter 2020) effectively ruling out any real analysis of fish movements. Instead, I was left with the worrying question of what has happened in the inner Oslofjord to cause such a rapid decline in the cod population. Also of paramount importance should be the general health and condition of the cod specimens caught during this study. 39 of 106 of individuals were found to be in poor physical condition (*k*-factor below 0.8) (Mello and Rose, 2005). A comparison of our results to the predicted weight of a healthy cod provides a very clear difference and indicates poor physical condition of Atlantic cod in the inner Oslofjord. Initial observations at the time of catch did indicate poor physical condition, with several fish being returned to the water immediately, untagged, to avoid physical stress, deemed unsuitable for tagging despite being well within predetermined size limits.

The results of this study indicate poor recruitment in recent years. This may point toward a failure of juvenile cod to find an adequate food supply. Climate-driven warming waters may have had a detrimental effect on an important prey species for young cod – the copepod *Calanus finmarchicus*, a constituent of zooplankton and a key component of the north Atlantic food web. Newly hatched cod larvae, around 3-4 cm long, depend on *C. finmarchicus* as an important starter feed while on the bottom as *C. finmarchicus* undergoes its six-month winter hibernation on the bottom. Since the 1990s, there has been a well-established connection between climate change and abundance of *C. finmarchicus* in the North Sea (Wilson, 2016). Data from 1960 onwards has shown the ratio of *C. finmarchicus* to *C. helgolandicus* (another copepod and constituent of zooplankton) in the Oslofjord to have shifted heavily in favour of *C. helgolandicus*. This copepod is most abundant during the spring and autumn and differs from *C. finmarchicus* in that only some overwinter on the bottom – those with sufficient energy stores to do so. The rest will remain at the surface throughout winter (Rey-Rassat et al. 2002, Bonnet et al. 2005). This may create a major problem as the seasonal cycles of the young cod and their primary food source are no longer a match. IMR beach seining data shows almost no zero-group cod found since 2012. This study did find individuals from each cohort class since 2012, raising a question as to why the IMR beach seining did not. However, the data from this study did somewhat support these IMR findings with a sharp decline from 2016 onwards, indicating that something is indeed inhibiting recruitment.

Warming waters may be having an effect on diel migrations. These happen at night when cod migrate to shallower depths to feed. These vertical movements could become limited to colder, deeper waters if surface temperature were to increase sufficiently. These migrations are more common in smaller cod, with the bigger individuals more influenced by changes in surface temperature and preferring to remain in the deeper waters where temperatures are lower (Freitas et al. 2015). It has been suggested that larger cod may be less adept at regulating their oxygen supply at higher temperatures (Freitas et al. 2015). Increased surface temperatures may drive larger cod to deeper water and where the smaller, more active cod would usually utilize the shallow waters to feed during their diel migrations in the summer, this may no longer be an option. The long-term effects of these changes on local populations may be severe. With these shallow summer feeding grounds unavailable, growth may be limited in these months. With larger fish being the more strongly affected, these conditions will suit the growth and survival of smaller individuals and could lead to evolutionary consequences where the survival of smaller fish is favoured. As a keystone species in most coastal areas of Norway, these potential evolutionary changes could have negative effects on local ecosystems and economies (Freitas et al. 2015). These effects may be evident in the results of this study, with large fish seemingly completely absent from the coastal cod populations within the inner Oslofjord. This will also have a profound effect on recruitment with the largest cod spawning for the longest amounts of time. This would also be supported by the data from this study, as well as the IMR beach seining data (Figure 17), with zero-group cod seemingly absent from 2013 onwards. However, results of this study also indicated that larger and older individuals are present in zone 3, whereas the youngest and smallest individuals were found in zone 2. This suggests that the older individuals are not being forced to deeper water. The differences in depth, salinity, and pollution would also have suggested that these results should have been reversed, with zone 3 closest to a major river outlet and seemingly the least suitable for survival of cod, particularly the larger individuals.

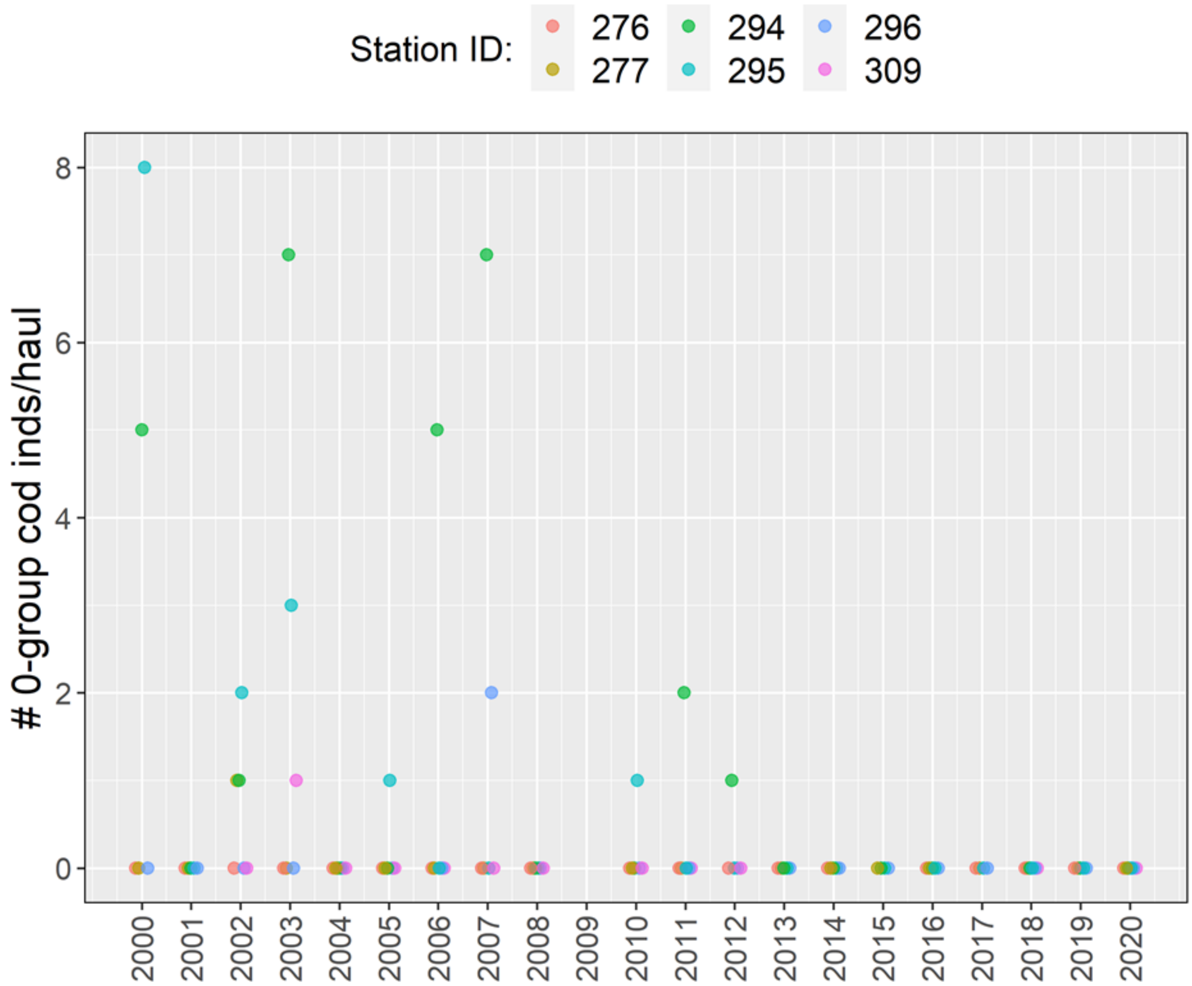


Figure 17. Zero-group cod numbers from IMR beach seining data collected from the six inner Oslofjord sampling zones that have been sampled since 1919. The annual values have been slightly spread to facilitate separation of sampling zones.

Low population figures, such as those indicated by the CPUE results in this study, may suggest that predators are having an impact on the population. In the case of Inner OsloFjord Atlantic Cod, predation from seals (Trzcinski et al. 2006) and birds is a specific threat. While little real information still exists on the role of seals in the inner Oslofjord, extensive research has been carried out on the effects of the grey seal population on the declining Atlantic cod population in the southern Gulf of St Lawrence in Canada (Cook et al. 2015) and (Hammill et al. 2014). While the seal population in the Oslofjord is not believed to be of sufficient size to have been a major factor in the decline of the coastal cod population, The Canadian studies would suggest that they may be a factor in their failure to recover.

Another predation risk comes from birds, particularly cormorants. Studies of the feeding habits of Norwegian cormorant populations have indicated that the diet of breeding cormorants consisted mainly of gadoids, mainly cod and saithe, with 0- and 1- group cod dominating throughout the first two years of the study. A decrease in the third year of the study could reflect the decrease in the Norwegian coastal cod population (Lorentsen et. Al., 2004). A different study on the diets of Shags and cormorants in Norway also concluded that the diets of both species rely heavily on small gadoids for food throughout their range and that this could be an important factor limiting the recruitment of cod in the declining populations (Barrett et al. 1990). The poor recruitment evident in both this study and recent IMR beach seining data (Figure 17) may suggest that juvenile cod are being heavily preyed upon by a predator, such as cormorants. However, the latest IMR report on the Oslofjord effectively ruled out predators (such as seals and cormorants) as drivers in the decline of the cod population (Espeland & Knutsen, 2018).

As an important commercial and recreational species, Atlantic cod has long been fished in the inner Oslofjord. Fishing mortality may be a factor in the collapse of the cod population, with fishing mortality a possible factor until an eventual fishing ban in 2019 (Kleiven et al 2016). The ban of 2019 will hopefully help the stocks to recover in time, but an important role in any recovery will be played by the oldest and biggest fish. As well as a severe decline in the size of the cod population altogether, it has also been evident that the size of the cod living in the fjord is in decline. The biggest fish appear to now be gone from the inner Oslofjord, creating a major problem for any potential recovery of the cod stocks. With the age structure of the cod stocks severely reduced, recovery of the population may be compromised as the older, larger cod tend to spawn for longer than the smaller fish and produce large numbers of good quality eggs (Myers et al. 1996). This study has indicated that fish from zones 1 and 2 do not live beyond 6 years whereas fish were found to have reached up to 8 years in zone 3. The similarities in physical factors such as location, bottom type, and depth between zones 1 and 3 would suggest that another factor may be influencing the age of the populations in these zones. My results would also suggest that the difference in water quality is not this factor. With zone 3 situated on the Sandvikselva side of Ostoya, water quality could have been expected to play a role here, however this does not appear to be the case as the largest and oldest individuals were found where the water quality should be considered least favorable. With specific methods of fishing having been shown to select for different sizes of fish (Ski, 2013), it is possible that specific types of fishing have been used in zones 1 and 2, selecting for older/larger fish, that are not being used in zone 3.

The poor recruitment seen in this study may indicate habitat changes. Juvenile cod and their prey species rely on kelp forests for shelter. In recent years certain important kelp species have been in decline in the inner Oslofjord. Main culprits for this decline may be pollution and/or climate change. Industrial disposal, sewage, and coastal runoff may all contribute to kelp forest degradation. Evidence has shown that marine forests have declined in many urban areas (Matsumoto et al. 2020). Coastal shores are experiencing an inflow of sediments and fine particles which can inhibit zoospore attachment and gametophyte growth through the decrease in availability of substrate and surface area for substance exchange. The effects are greater as particle size decreases, and this is a particular problem during early-stage growth of the plant (Matsumoto et al. 2020). With this habitat in danger, juvenile cod may struggle to find both shelter and food. This not only leaves them vulnerable to predation but will hinder growth and survival. If this is the case in the inner Oslofjord I would expect to see the poorest numbers in zone 3 where municipal pollution should be highest, but this does not appear to be the case.

This study has identified bottom type and season as the main factors influencing catch per unit effort (CPUE), with a soft bottom type (sand, silt, and mud) seemingly strongly favored above gravel or hard/rocky bottom types throughout autumn, winter, and spring. The autumn periods were much more successful in terms of CPUE than winter and spring. One slight exception was winter 2019 which showed slightly higher numbers than spring and winter of 2020. There was very little evidence of any seasonal pattern in habitat preference, with soft bottom preferred over the others and hard preferred over gravel in each season. These findings on bottom type and season are somewhat contrary to the findings of several previous studies that have ascertained that adult Atlantic cod tend to have a preference for more coarse sediments, such as gravel or stone over fine sediments such as sand, mud, and silt, with many adults typically found along rocky slopes on or near the bottom (Fahay, 1999). Another study in the Belgian part of the North Sea (Reubens et al. 2013) found adult Atlantic cod to prefer hard substrates and structures, and in this particular case many fish being present around artificial reefs particularly in autumn and summer. The same study also identified a clear seasonal pattern in habitat preference and noted a particularly high number of fish present in autumn and summer compared to very low numbers in winter (Reubens et al. 2013). That particular study was focused on artificial reefs and hard structures, but the results would still appear to be contrary to my results, which showed a clear preference for soft bottom no matter what season. Analysis of bottom type across the gradient of the three sampling zones was difficult due to the high degree of variability in bottom type throughout and between each zone. Under these circumstances I must consider the possibility that catchability could be a factor in our results, and that cod may be more easily trapped when the trap is placed on a soft, flat surface rather than an uneven, rocky one where undulations/rocks/vegetation may not only provide shelter for the fish but may hinder accurate trap placement. I must consider that CPUE may be a poor proxy for abundance owing to catchability that may vary in time, space and due to both extrinsic factors (weather, tempetarure, prey availability, predators etc.) and intrinsic factors (size of fish, sex, habitat use, feeding motivation etc.) (Arreguín-Sánchez, 1996). Also of note, however, are the findings of a trawling time series (2010 to 2021) from Steilene inner Oslofjord that shows an alarming decline in cod CPUE since 2014 (Hyland, 2012).

A particularly striking result of this study was the physical condition of the fish caught over the two years of trapping. These results, presented as condition factor (Fulton's *k*-factor), showed that on average the fish caught in spring were in the best physical condition (0.98) and those caught in autumn to be in the poorest physical condition (0.76) with winter in between (0.81). Studies have shown that cod should be in their poorest physical condition in spring, during the spawning season, and should rapidly gain weight in the post spawning period to be in their peak physical condition in autumn (Mello and Rose, 2005, Herland et al. 2010). While our results suggest the opposite of this, I must consider that many females may still be carrying eggs in spring that may account for 25 % of their body mass. These numbers still indicate poor physical condition all year round and the low catch numbers make it more likely that one or two particularly poor physical specimens will impact more strongly on the averages. The autumn 2020 catches from zone 1 would back up this theory, with three of the four fish caught being in extremely poor physical condition.

Figure 14. Cod with different Fulton's condition factors. Age was determined with annuli counting of the otolith. The total length of the specimen is presented in the brackets (A) A cod with *k-factor* = 0.95, age 6 years (B) A cod with *k-factor* = 0.84, age 2 years (C) The cod with the lowest *k-factor* = 0.61, age 3 years.
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The poor physical condition of the majority of the majority of individuals sampled in this study might point towards poor food availability which may, in turn, indicate poor water quality or environmental conditions. Pollution has long been a problem in the waters of the inner Oslofjord. This has been a documented issue since the beginning of the 20th century. Originally identified in the 1930s around sewage outlets, measures have been taken over the decades, including activated sludge when organic matter was considered the major problem, but municipal sewage continues to be an issue to this day as the population of Oslo continues to grow – increasing the impact area of municipal wastewater (Arnesen, 2001). A major factor influencing water quality in the inner Oslofjord is the fact that it is separated from the outer Oslofjord by Drøbak sound which has a maximum depth of around 27 m. This prevents good water circulation between the inner and outer parts of the Oslofjord, leaving the inner Oslofjord vulnerable to nutrient loading and causing anoxic conditions in the deeper areas (Arnesen, 2001). The results of this study, interestingly, may indicate that pollution/water quality may not be as big of a factor as initially expected. With no significant river outflow, zone 2 was expected to have the best water quality with the least municipal pollution and least dilution from fresh water flowing into the fjord, whereas zones 1 and 3 were expected to suffer from more pollution from the land and more dilute water due to a major river outflow. Despite this, back-calculated length data shows that fish from zone 2 have clearly the lowest size at age of the three zones, indicating that water quality may not have had the expected effect on growth in these zones. Fish from zones 1 and 3 have similar size but those from zone 3 appear to be living much longer than the other zones. While growth and life expectancy were found to be the lowest in zone 2, condition factor was on average the highest. Fish in zone 2 were found to have weights closest to expected weight, despite still being below.

Figure X. Cod in poor condition caught in zone 3 on 1st of December 2019. Many individuals had these winter wounds most likely (but not confirmed) caused by the bacteria Moritella viscosa.

For more than a decade, studies have been carried out on thiamine (Vitamin B1) levels in a range of animal classes to determine whether thiamine deficiency complex (TDC), could be the cause of a wide range of physical impairments including growth, condition, blood chemistry, endurance, and reproduction (Balk et al. 2016). Several of these studies have been focused on Baltic cod, whose population and condition indices have been decreasing for the last 30 years (Engelhardt et al. 2020). Thiamine levels in these cod have been shown to be deficient in the brain and liver in 77 % of individuals – severely in 64 % and 13 % respectively. In the same study, only 2 % of individuals were found to have a healthy condition factor and 49 % were found to have a condition factor of less than 0.8 which indicates poor health status. The common outcome of TDC tends to be high mortality at early life stages (Harder et al. 2018). Incidences of thiamine deficiency appear to be increasing and the reason for this is not clear. Studies have suggested evidence pointing to consumption of the thiamine degrading enzyme thiaminase (Harder et al. 2018) or insufficient amounts of thiamine in food (Balk et al. 2016).

The poor-condition results of this study would appear correlate with the results of Baltic cod studies on thiamine deficiency. The particularly low condition factor observed in the majority of individuals, could indicate a thiamine deficiency, as could the apparent recruitment failure in recent years seen in the results of this study as well as the IMR beach seining data. This topic was not a focus in this study, but results would suggest that it may be relevant and that any future study of this kind should take blood samples in order to properly investigate.

Conclusions

This study has become an investigation of a seemingly rapidly declining population where the physical condition of individuals is consistently poor. CPUE has dropped by 70 % from 2011-2012 to 2019-2020. Contrary to what I expected, there was no visible trend across the gradient of the three sampling zones in terms of CPUE or physical condition. Trends in season and bottom type were identified but were inconclusive. Reasons for the population decline and poor body-condition are difficult to determine and could be varied and complex with habitat destruction, regime shift, predation, warming water, and over-fishing all possible culprits. There is a particularly compelling argument for a thiamine deficiency in the fjord cod population in the inner Oslofjord. I did not study this and to fully understand the general poor condition of this population, it would be recommended that any further study of this kind take blood samples to further investigate this.

Based on the results of this study, there is little evidence so far that the cod fishing ban in the inner Oslofjord has helped the population to recover thus far. Other management strategies may be required to protect this population, but a deeper understanding of the issue through continued study will be essential to pinpoint the biggest issues.

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Appendices

Length, weight and condition factor of each cod caught, by zone and season. Fish measuring less than 30cm in length are excluded from this as they were returned after measuring only length.

Zone 1		
Autumn 2019		
Length	Weight	Condition Factor
47	830	0.799437504
42	600	0.809847749
65	2300	0.83750569
54	1350	0.85733882
57	1600	0.863963541
46	850	0.873263746
50	1120	0.896
Winter 2019		
Length	Weight	Condition Factor
44	740	0.868707739
60	2300	1.064814815
57	1690	0.91256149
46	950	0.976000658
64	1470	0.560760498
60	2500	1.157407407
Spring 2020		
Length	Weight	Condition Factor
65	2170	0.790168411
46	1070	1.099284951
Autumn 2020		
Length	Weight	Condition Factor
57	700	0.377984049
31	250	0.839179618
66	1000	0.347830926
31	110	0.369239032
Winter 2020		
Length	Weight	Condition Factor
64	1800	0.686645508
47	600	0.57790663
34	120	0.305312436
60	1600	0.740740741
66	2300	0.800011131
37	300	0.592265019
56	840	0.478316327
35	230	0.536443149

Zone 2		
Autumn 2019		
Length	Weight	Condition Factor
47	1050	1.011336602
49	1020	0.866985695
55	1440	0.865514651
49	980	0.832986256
54	1550	0.984351979
45	1240	1.360768176
45	870	0.95473251
34	450	1.144921636
30	330	1.222222222
53	1500	1.00754314
34	350	0.890494606
42	700	0.944822373
Winter 2019		
Length	Weight	Condition Factor
50	1420	1.136
41	570	0.82703385
47	850	0.818701059
Spring 2020		
Length	Weight	Condition Factor
65	2460	0.895766955
60	1820	0.842592593
48	930	0.840928819
66	3000	1.043492779
37	640	1.263498707
57	2400	1.295945311
63	2500	0.999812035
49	1300	1.104981768
Autumn 2020		
Length	Weight	Condition Factor
57	1020	0.550776757
34	250	0.636067576
36	340	0.728737997
59	1700	0.827737987
55	1100	0.661157025
40	390	0.609375
31	250	0.839179618
60	1600	0.740740741
44	620	0.727836213
32	250	0.762939453
35	420	0.979591837
Winter 2020		
Length	Weight	Condition Factor
45	650	0.713305898
39	410	0.691178206

Zone 3		
Autumn 2019		
Length	Weight	Condition Factor
62	2650	1.111912994
61	1750	0.770989642
49	1230	1.04548275
56	1840	1.047740525
62	2000	0.839179618
70	2900	0.84548105
47	1110	1.069127265
65	2400	0.87391898
60	1800	0.833333333
54	1000	0.635065793
47	800	0.770542173
48	800	0.72337963
71	3100	0.866137112
Winter 2019		
Length	Weight	Condition Factor
54	1600	1.016105269
66	2050	0.713053399
50	1000	0.8
55	1400	0.841472577
52	1018	0.723998635
50	1110	0.888
58	1740	0.891795482
57	1410	0.76136787
48	930	0.840928819
58	1650	0.845668129
63	1970	0.787851884
Spring 2020		
Length	Weight	Condition Factor
70	3310	0.965014577
61	1810	0.797423573
40.5	600	0.903204683
53	1480	0.994109231
59	2360	1.149095088
68	2760	0.877773255
48	1030	0.931351273
Autumn 2020		
Length	Weight	Condition Factor
60	1880	0.87037037
65	2500	0.910332271
57	1590	0.858563769
47	470	0.452693526
34	310	0.788723794
31	80	0.268537478
68	2320	0.737838388
55	540	0.324567994
51	600	0.452314721
66	1300	0.452180204
Winter 2020		
Length	Weight	Condition Factor
53	1300	0.87

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