

Tallknusing av miljøovervåkingsdata



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Abstract Natural populations are affected by a range of factors, including climate and contaminants. In this study, we have used use data from both population monitoring as well as contaminant monitoring to analyse variation in abundance of Atlantic cod on the coast of Skagerrak and black-legged kittiwake in mainland Norway. For Atlantic cod, we found significant effects of both climate (temperature and wind) as well as contaminants (concentrations of HCH-A, HCB and PCB-153 in blue mussels). For black-legged kittiwake, a population model confirms that for the southerly populations Runde and Sklinna, either adult survival is lower than in more northerly populations, or that chicken mortality is extremely high (~95%).
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Tallknusing av miljøovervåkingsdata

Effects of climate and pollution on Atlantic cod and
kittiwake populations

Preface

This study is written on behalf of the Norwegian Environment Agency (Miljødirektoratet). In 2013, the Norwegian Environment Agency was created by fusion of the two previous institutions Norwegian Directorate for Nature Management and the Norwegian Climate and Pollution Agency. The Norwegian Environment Agency is committed to combine data sets from different sources, such as contaminant data together with population monitoring data. The goal of the present project was to use monitoring data in order to investigate which factors, including climate and contaminants, that are important for population trends, using Atlantic cod and black-legged kittiwake as case studies. The principal investigator has been Dag Ø. Hjermann, while Katrine Borgå, Anders Ruus and Hege Gundersen from NIVA contributed with collecting data and writing. Halvor Knudsen and Esben Moland Olsen at the Institute of Marine Research at Flødevigen contributed as subcontractors with data delivery and on commenting on the text.

Oslo, 4. December 2013

Dag Øystein Hjermann

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Summary

Natural populations are affected by a range of factors, both natural (such as variation in food availability and abundance of predators), anthropogenic factors (such as contaminants) and partly anthropogenic factors (for instance, climate varies naturally but is also affected by emissions of greenhouse gases). In this project we have studied two species, Atlantic Cod (*Gadus morhua* L.) and Black-legged Kittiwakes (*Rissa tridactyla* L.), and used data from both population monitoring as well as contaminant monitoring to analyse statistically how the variation in the abundance of these species correlates with climate and contaminants. We focused on Atlantic cod on the coast of Skagerrak (including the Oslofjord), and on black-legged kittiwake in mainland Norway. By and large, these groups of populations have declined strongly the last decades. Both species have also declined in the North Sea region, and the cod has also declined along the Swedish parts of Kattegat and Skagerrak.

In the case of Skagerrak cod, our main population data was abundance of approximately half-year old cod from the annual beach seine survey of Institute of Marine Research. These data consists of counts of juvenile cod for every autumn since 1919 (except for the Second World War) in a large number of localities from Torvefjord (west of Kristiansand) to Oslo. Data from different regions show differences in population development over time. South of the Grenland area, the abundance of cod juveniles went down until c. 1950, increased to a peak in the 1960s and then declined. North of the Grenland area the populations reached a peak in the 1950s, a trough in the 1980s and has since then increased somewhat, except in Hvaler, where numbers have levelled out on a relatively low level. The lowest abundance of juvenile cod is presently found in the two areas with a high degree of contamination, Grenland and Inner Oslofjord. In the latter area the abundance of juvenile Atlantic cod has been low since the start of the survey, while Grenland had the highest abundance of all areas in the 1950s, and then declined steeply to reach a very low level in the 1980s. Since then, the populations have recovered a bit. We analysed these data in two ways: (1) a statistical time series analysis showed a strong correlation between Atlantic cod recruitment and several measures of climate. The areas north and south of Grenland were mostly affected by the same variables: recruitment was high in years with a high air temperature and off-shore winds in spring (especially in the northern region), and with cool weather and along-shore wind from the NE in the autumn (especially in the southern region). In addition, cod in the Northern area appeared to be negatively affected by high values of the North Atlantic Oscillation (NAO). These findings are supported by some previous papers, and are likely to be caused by variations in recruitment, but influx of cod larvae from the North Sea may also play a role. (2) We focused on effects of interannual levels of 8 contaminants in blue mussels from 4 areas where there also were beach seine stations nearby. Of those 8 contaminants, there was an indication of a negative effect of contaminant concentration for 3 contaminants (HCH-A, HCB and PCB-153). The report also discusses possible extensions using other sources of data.

For black-legged kittiwakes, an analysis of a population model indicates that key parameters are mean adult survival and variation in chick survival. The population development of two colonies (Runde and Sklinna) is difficult to explain using typical survival values (for chicken and adults) from studies from more northerly sites. This confirms that either adult survival is lower than in the northerly populations, or that chicken mortality is extremely high (~95%). It is also possible that subadult mortality (mortality from fledging to first breeding) is substantially higher than adult mortality. The kittiwake part of this study was weakened by not getting access to all existing data.

In conclusion, there are strong indications that Skagerrak Atlantic cod stocks are affected by both interannual climate variations and local contamination. The climate variables used show long-term trends, especially since 1980, some of which have a negative effect on Atlantic cod. There appears to be negative effects of local contamination in Grenland, even if industrial release has practically ceased. The two black-legged kittiwake colonies we have studied show a steep decline (one has become extinct), so fast that either adult survival is substantially lower than in other (more northerly) colonies, or that chick survival is close to zero in almost all years. While the cod data has large year-to-year fluctuations, the black-legged kittiwake colonies we have studied show less year-to-year variation, and therefore statistical analysis of time series has a smaller potential for indicating significant factors.

Sammendrag

Naturlige populasjoner er påvirket av den rekke faktorer, både naturlige (eks. variasjoner i mattilgang og predatorer), menneskeskapte faktorer (eks. miljøgifter), og delvis menneskeskapte faktorer (eks. klima, som naturlig svinger men også påvirkes av utslipp av drivhusgasser). I dette prosjektet har vi studert to arter - torsk (*Gadus morhua* L.) og krykkje (*Rissa tridactyla* L.) - og bruker data fra både populasjonsovervåking og miljøgiftovervåking til å analysere statistisk hvordan variasjoner i antall av disse artene korrelerer med klima og miljøgifter. Populasjonene vi fokuserte på var torsk på kysten av Skagerrak (Sørlandet og Oslofjorden) og krykkje i fastlands-Norge. Begge disse populasjonsgruppene har gått tilbake over lengre tid. Begge artene har også gått tilbake i Nordsjøen, og for torskens del også i Kattegat og langs den svenske Skagerrakkysten.

For Skagerrak-torsk var hovedkilden vår data på yngel (ca. et halvt år gammel) torsk fra Havforskningsinstituttet avd. Flødevigen sitt strandnottokt. Hver høst siden 1919 (med et avbrekk under 2. verdenskrig) har antall torskeyngel blitt telt i strandnotttrekk på ulike lokaliteter fra Torvefjorden (vest for Kristiansand) til indre Oslofjord. Data fra ulike regioner viser ulike utviklingstrekk over tid. Sør for Grenland gikk mengden torskeyngel ned fram til 1950, nådde en topp på 1960-tallet, og har senere avtatt. Nord for Grenland nådde populasjonene en topp på 1950-tallet, en bunn på 1980-tallet, og har senere økt noe - med unntak av Hvaler, der populasjonene har flatet ut på et relativt lavt nivå til dette området å være. De to områdene med sterk påvirkning av forurensing, Grenland og indre Oslofjord, har lavest mengde torskeyngel av alle områder. I indre Oslofjord har mengden torskeyngel alltid vært lav, mens Grenland hadde den høyeste mengden torskeyngel av alle områder på 1950-tallet, men mengden stupte til et meget lavt antall rundt 1980, for siden å ta seg opp noe (men mengden torskeyngel er fremdeles meget lav). Vi analyserte disse dataene på to måter. (1) En statistisk tidsseriemodell viste at klimavariabel hadde sterk samvariasjon med rekrutteringen til torsk. Vi fant at det var de samme klimavariablene som påvirket rekrutteringen nord og sør for Grenland: rekrutteringen var høy i år med høy lufttemperatur og fralandsvind i larvenes oppvekstperiode på våren (særlig i nord), og når det var kjølig vær og vind fra nordøst på sensommeren og høsten (særlig i sør). Nord for Grenland var det i tillegg dårlig rekruttering i år etter milde vintre (høy indeks av NAO, den Nord-Atlantiske Oscillasjon). Disse funnene støttes delvis av tidligere resultater, og skyldes trolig faktisk variasjon i rekruttering, men kan også være påvirket av tilførsel av torskelarver fra torsk i Nordsjøen. (2) Vi så på effekt av forurensing i fire områder der en hadde faste strandnotttrekk i samme område som en hadde gode tidsserier på miljøgifter i blåskjell. Av de 8 miljøgiftene vi studerte, var det en indikasjon på en negativ effekt av den årlige konsentrasjonen av 3 miljøgifter (HCH-A, HCB og PCB-153). Rapporten diskuterer ulike måter og data som kan brukes til å utvide analysen.

For krykkje viser en modell for utviklingen til krykkjekolonier at to nøkkelparametere er gjennomsnittlig overlevelse hos voksne og variasjon i overlevelse hos unger (fra egg til flyvedyktig alder). Utviklingen av koloniene på Runde og Sklinna, der populasjonene går sterkt tilbake, kan ikke enkelt forklares om en bruker typiske verdier for unge- og voksenoverlevelse fra populasjoner lenger nord (der en har data på voksenoverlevelse). Dette bekrefter at enten er voksenoverlevelse lavere enn den er for populasjoner lenger nord (der en har data på voksenoverlevelse), eller dødeligheten hos unger er konstant svært høy (~95%). En mulighet er også at dødeligheten av juvenil fugl (fra de er flyvedyktige til første reproduksjon) er vesentlig høyere enn hos voksne. Denne delen av undersøkelsen ble svekket av at vi ikke hadde vi tilgang på alle data som er samlet inn.

Vi konkluderer med at det er sterke indikasjoner på at torskepopulasjonene på kysten av Skagerrak påvirkes både av klimavariasjoner og lokal forurensing. Klimavariablene har langtidstrender, særlig siden 1980, og noen av disse synes å påvirke torsken negativt. Det later til at torsken i Grenlandsområdet fremdeles er påvirket negativt av lokal forurensing, selv om utslipp fra forurensende industri har mer eller mindre stoppet. De to krykkjekoloniene vi har studert har rask nedgang (den ene ble helt forlatt etter 2010-sesongen), så rask at den tyder på at enten voksenoverlevelse er betydelig lavere enn hos andre (mer nordlige) studerte populasjoner, eller at ungeoverlevelsen er nær null i nesten alle år. Mens torsken preges av store å-til-år-variasjoner, later det til at de krykkjepopulasjonene vi har studert er mindre preget av år-til-år-variasjoner, noe som gjør at statistisk analyse av tidsserier har mindre potensiale for å påvise signifikante forklaringsvariable.

1. Introduction

The purpose of this study was to investigate which environmental factors that affects the development of Norwegian populations of Atlantic cod (*Gadus morhua* L.) and all black-legged kittiwake (*Rissa tridactyla* L.). The goal of the project was to answer

- which data are available and which data are necessary to achieve this purpose=
- what is the current situation of the populations, and how have these populations developed over time?
- which environmental factors (climate, contaminants, harvest) influence the observed population development?
- which environmental factors are most strongly correlated to the observed population development?
- which other links between environmental factors are most important?
- how far are we from explaining the population development based on available time series and what are the important knowledge gaps?

We focused this study on two sets of populations: (1) for Atlantic cod, the populations on the Norwegian Skagerrak coast, and (2) for the kittiwake, two populations on the Norwegian mainland. In both cases, these populations have declined severely for a number of years, and the reason for the decline is unclear. With this study, we use analyses of available data to try to shed some more light on which processes that may be of importance, in particular effects of climatic fluctuations and pollution.

Atlantic cod (*Gadus morhua* L.) has declined on the Norwegian Skagerrak coast (Fig. 1), at least from Kragerø and eastwards. This mirrors the decline of Atlantic cod stocks in the nearby areas of the North Sea (Cook et al. 1997) and the Swedish Skagerrak and Kattegat coasts (Svedäng & Bardon 2003). The Atlantic cod along the Norwegian Skagerrak has been the focus of a unique long-term survey, the beach seine survey, which started in 1919 and is still continued today using basically the same gear and techniques. The data are collected every autumn, and the data set covers a large number of stations over a distance of almost 300 km. It has been the focus of several studies of population dynamics, in particular from 1997 to 2001 (see Fromentin et al. 2002 and references therein). This study builds in part of those previous studies. It differs from them by also focusing on possible effects of climate and pollution in the Grenlandsfjord area, which was heavily polluted in the period 1951-2000. In this study, we perform two types of analyses: (1) an analysis of the fluctuations of young (half year old) Atlantic Atlantic cod in all sampling stations with at least 20 years of data, and (2) a study on relationships between Atlantic Atlantic cod and pollution for a limited number of stations close to pollution monitoring stations.

The causes of fluctuations and trends in Atlantic cod stocks, and in particular changes in recruitment, have been the subject of a vast number of studies since the seminal work of Hjort (1914). In general, cod recruitment has been linked to

- interannual variations in temperature, depending on latitude (positive correlations for northerly populations, negative correlations for southerly ones)
- interannual variations in the winter North Atlantic Oscillation (NAO), whose effect also depends on latitude or mean temperature
- whether the larval stage of cod occurs during the spring bloom (the match-mismatch hypothesis of David Cushing), and

- Juvenile Atlantic cod are more abundant in complex areas, particularly in shallow water eelgrass beds, which have been found to reduce predation rates on cod (Gotceitas et al. 1997, Grant & Brown 1998, Gorman et al. 2009)

For the North Sea, the decline in Atlantic cod has been linked to

- overfishing (Cook et al. 1997)
- declining recruitment due to a decline of the zooplankton *Calanus finmarchicus* (a key food for larval cod) caused by higher temperatures (Beaugrand et al. 2003, Beaugrand 2004). This species has been replaced by *C. helgolandicus*, which is abundant at a different time of year and for that reason not suitable for the cod larvae, and
- possible effects of herring predation on cod eggs (Fauchald 2010, Hjermmann et al. 2013)

For Atlantic cod in the Skagerrak, some important findings of earlier studies include:

- There is genetic evidence that populations in each fjord are quite isolated (Olsen et al. 2004, Jorde et al. 2007). This is possible because the adult Atlantic cod is relatively stationary (Espeland et al. 2008) and because the water circulation inside the fjord sills prevents eggs from escaping the fjord (Knutsen et al. 2007, Ciannelli et al. 2010).
- Genetic evidence, supported by analyses of oceanographic models, indicates that there is a significant influx of eggs/larvae from North Sea populations of Atlantic cod in years with particular oceanographic current patterns (Knutsen et al. 2004, Stenseth et al. 2006)
- The length of juvenile cod is positively affected by spring temperature but negatively affected by summer temperature (Rogers et al. 2011)
- Predation from cormorants (great cormorant *Phalacrocorax carbo*) and seals (harbour seal *Phoca vitulina*) may be substantial and has been suggested to be a leading cause for decline of adult cod in the northerly part of Skagerrak (Gjøsæter & Danielssen 2004)
- In Kattegat and the Swedish side of Skagerrak, there are clear indications that overfishing is the prime reason for the decline of cod (Svedäng & Bardou 2003, Cardinale & Svedäng 2004)

Thus, there are clearly a lot of hypotheses that could be studied with regard to the trends of Skagerrak Atlantic cod. For the present study, we wanted to explore what the beach seine survey data can tell us about small-scale variation in cod abundance, in particular in relation to variations in climate and contaminants. For a discussion of other data sets and approaches we refer to Chapter 2.5.

Almost all black-legged kittiwake (*Rissa tridactyla* L.) colonies of mainland Norway has declined during the last 20-30 years (Anker-Nilssen et al. 2013). While the numbers of the species still are high – more than 150 000 pairs in 2008 (Anker-Nilssen 2009) there is concern that the black-legged kittiwake (as other seabirds) acts as a "canary in the mine" indicating deteriorating health of marine ecosystems. The fact that the species has declined severely also in the North Sea area (Frederiksen et al. 2004) adds to this concern. Regarding the black-legged kittiwake, the availability of data was much smaller than for cod, and we focus on two populations for which some population data is publicly available (Fig. 1). We use population models, together with available information on the range of population parameters, to explore the possible effects of chick mortality and adult mortality.

The black-legged kittiwake went through an increase (range expansion) throughout Europe, including Norway, during the 1960s (Barrett 1994). In the North Sea area, it has strongly decreased the last decades (Wanless et al. 2007), which has been linked to industrial fisheries of pelagic fish, the black-legged kittiwake's key prey as well as increasing sea temperatures

(Frederiksen et al. 2004, 2005). In Norway, the species is red-listed in category EN (endangered) due to reductions between 63% and 86% of the monitored populations between 1980 and 2010. The black-legged kittiwake is also red-listed in the Faroes and Greenland. The species' breeding success in Norway is linked to food availability (Barrett 1996, 2007, Barrett & Krasnov 1996).

Due to the time limits of the present study, we needed to focus on a few elements for the actual statistical analyses. For Atlantic cod, we did two analyses: one time series analyses for most stations, focusing on effects of climate, and one analysis that focused on effects of contaminants in a subset of the cod stations. For black-legged kittiwakes, we focused on how the predictions of a simple population model, parameterized with data from Norwegian kittiwake colonies, compares with the actual population development of the two focal colonies.

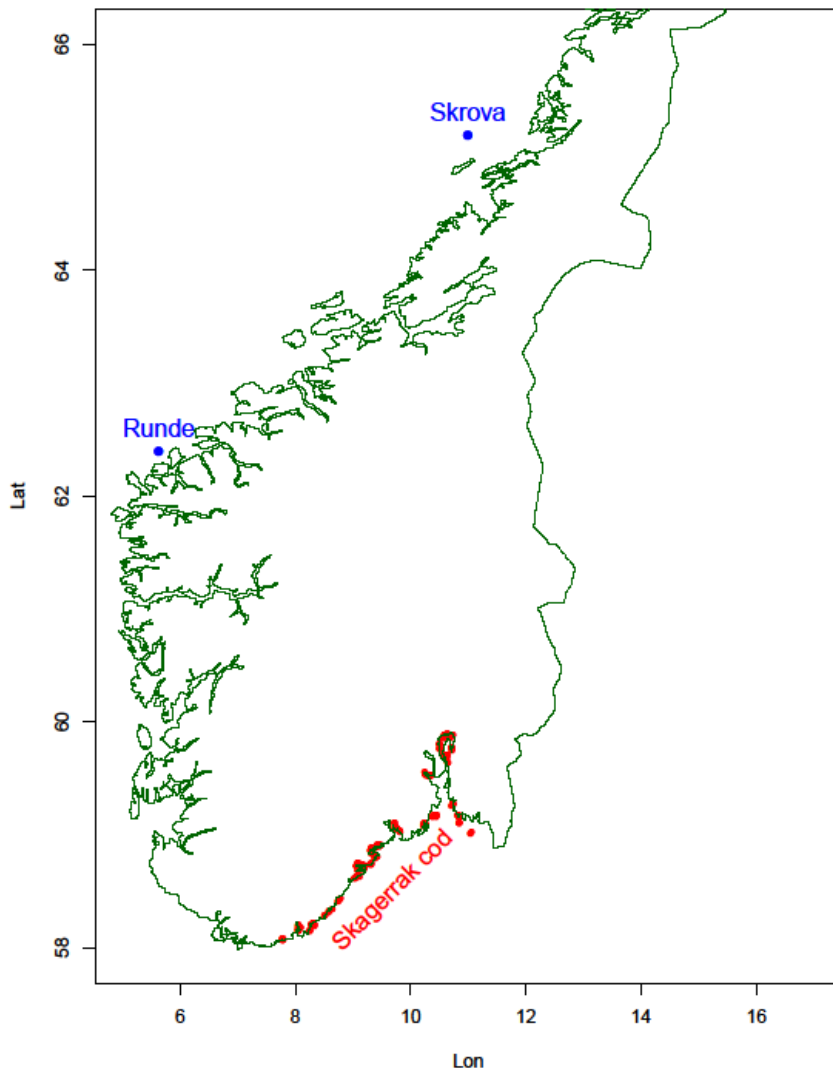


Figure 1. Map of the study populations of Atlantic cod (red) and black-legged kittiwake (blue).

2. Atlantic cod on the Skagerrak coast

2.1 Data

2.1.1 Abundance in the beach seine survey (no.: "strandnottrekk")

The Atlantic cod individuals collected by this survey consist mainly of 0-group Atlantic cod (less than one year old Atlantic cod) and 1-year old Atlantic cod. The sampling stations are spread along the coast from Torvefjord (west of Kristiansand) to Oslo, as well as some samples on Hvaler i Østfold county (Fromentin et al. 1997). Sampling in the 1920s and 1930s included only the southernmost part (Vest-Agder, Aust-Agder and Telemark), while sampling further north started later (in 1936; see Fig. 2). Sampling in the Grenlandfjord area, which later became very polluted, started in 1951. During the Second World War, only a few stations were sampled. For this study, we used only stations with at least 20 years of data and whose geographic position was exactly known, which leaves us with 140 stations in 21 different fjords/areas (Fig. 2).

2.1.2 Pollution data

We used data on contamination in Atlantic cod from the program "Contaminants in Coastal Areas" (Miljøgifter i Kystområder, MILKYS; the data also includes data collected in the preceding program, CEMP). There are also additional contamination data from the Norwegian Program for Pollution Monitoring (Statlig Program for Forurensingsovervåking), that was not used here (see section 2.5). We supplemented the data on cod with data on contamination in blue mussels (*Mytilus edulis*), which to some degree should reflect contamination in the Atlantic cod's habitat and which greatly increases the data coverage in time and space.

2.1.3 Climate data

For regional climate, we used the station-based *winter NAO* (North Atlantic Oscillation) index for the previous winter (Dec-March; downloaded from NOAA National Weather Service Climate Prediction Center) and the annual value of the *AMO* (Atlantic Multidecadal Oscillation; downloaded from NOAA Earth System Research Laboratory). NAO and AMO are climatic indices of fluctuations in atmospheric pressures and sea surface temperature, respectively, and have been proved to correlate with a large number of ecological time series including cod population development (Stige et al. 2006). Typically, high NAO values indicate periods of mild winters in Northern Europe, with strong westerly winds across the Atlantic, whereas low values are typical of cold winters in Northern Europe.

At the local level, we extracted data (collected three times per day) on air temperature and wind from Torungen lighthouse, close to Arendal, which is likely to be representative for the coast (downloaded from eklima.met.no). For the wind data, we calculated the onshore (u) and alongshore (v) wind components (using 131 degrees as the onshore-offshore direction). We then calculated the onshore (τ_x , in figures referred to as "tau.x") and along-shore wind stress (τ_y or "tau.y") using the formulae

$$\tau_x = \rho_a c_D (\sqrt{u^2 + v^2}) u$$

$$\tau_y = \rho_a c_D (\sqrt{u^2 + v^2}) v.$$



Figure 2. Abundance of Atlantic cod in all stations (y axis) over time (x axis). The legend shows $\ln(\text{population size})$. The stations are ordered from the stations closest to the Swedish border, via the Oslofjord, to the southernmost stations.

which are the wind variables that are most likely to influence the oceanographic conditions on the coast (Ottersen & Sundby 1995). For instance, wind from the NE (along-shore wind stress) will result in accumulation of water along the coast by Ekman transport (Mann & Lazier 2006). For each of these three variables (temperature, onshore, and along-shore wind stress), we calculated the mean during two periods: spring (March-April, which represents the period of the important settlement stage of the Atlantic cod larvae) and autumn (August-September, which is the period up to the time of the beach seine survey), making a total of six variables for local weather. For periods where there was no acceptable wind data from Torungen (1919-1937 and 1943-1953), we used data from Færder, where we calculated the same variables, and then used the predicted values from a linear regression for the period with data from both locations to fill in the missing data.

2.2 Methods

On the level of the individual beach seine, the data on Atlantic cod older than one year have challenging statistical properties; in particular, they contain a large proportion of zeros. For this reason, we focused on the data on 0-group Atlantic cod. As we were especially interested in effects of pollution in different areas, we estimated time trends in five regions (Fig. 3): South (south of the Grenland area), Grenland (the Grenland fiord system), North (north of the Grenland area, with the exception of Oslo and Hvaler), Oslo (the inner Oslo fjord) and Hvaler (the Hvaler islands). Of these regions, two were thought to be particularly influenced by contaminants (Grenland and Oslo), one area is affected by high nutrient levels from the main river Glomma (Hvaler), and the two final areas (South and North) were thought to be less affected by either contaminants or major rivers. We used Generalised Additive Modelling (GAM) to estimate time trends for each region.

For the time-series analysis, we included Oslo and Hvaler in the North region. Our approach was based on so-called "gradient matching" (Ellner et al. 2002), which is a method that lets the modeler to incorporate reliably known aspects of the system (including parametric rate equations when these are justified), but to let the data "speak for themselves" about aspects that are less well known. These models have been called "semi-mechanistic". In gradient matching, one usually uses data on the adult population to infer the recruitment process (as data on the young stages are missing). In our case, we had data on young stages but not on the older ones, so we did the opposite. We assumed the Atlantic cod stocks in each fjord to be practically isolated from other fjord stocks, while the eggs and larvae probably are well dispersed within each fjord. Furthermore, we assumed the 2- and 3-year old Atlantic cod to be mature, and that adult survival is relatively constant. Then we can set up the following model

$$\begin{aligned} \log(R_{t,i}) &= b_{i0} + b_{i1} \cdot \log(M_{t,k}) + b_{i2} \cdot X1_t + b_{i3} \cdot X2_t + \dots + \varepsilon_{it} & (\text{eq. 1}) \\ N1_{t,i} &= s_{0-1} \cdot R_{t-1,i} \\ N2_{t,i} &= s_{1-2} \cdot N1_{t-1,i} \\ N3_{t,i} &= s_{2-3} \cdot N2_{t-1,i} \\ M_{t,k} &= \sum_{i=1}^{S_k} (N2_{t,i} + N3_{t,i}) \end{aligned}$$

where $R_{t,i}$ is the number of recruits (0-group Atlantic cod) at time t in station i , $M_{t,k}$ is the number of mature Atlantic cod in fjord k , and $X1_{t,i}$, $X2_{t,i}$, \dots are environmental variables. The error ε_{it} is assumed to be normally distributed. $N1_{t,i}$, $N2_{t,i}$ and $N3_{t,i}$ is the number of fish of age 1, 2 and 3, respectively, s_{0-1} , s_{1-2} , and s_{2-3} is the annual survival between age 0-1, 1-2 and 2-3. Finally, S_k is the number of stations in fjord k . From this, it follows that

$$\log(R_{t,i}) = b_{i0} + b'_{i1} \log[\sum_{i=1}^{S_k} (R_{t-2,i} + s_{2-3} \cdot R_{t-3,i})] + b_2 X1_t + b_3 X2_t + \dots + \varepsilon_{it} \quad (\text{eq. 2})$$

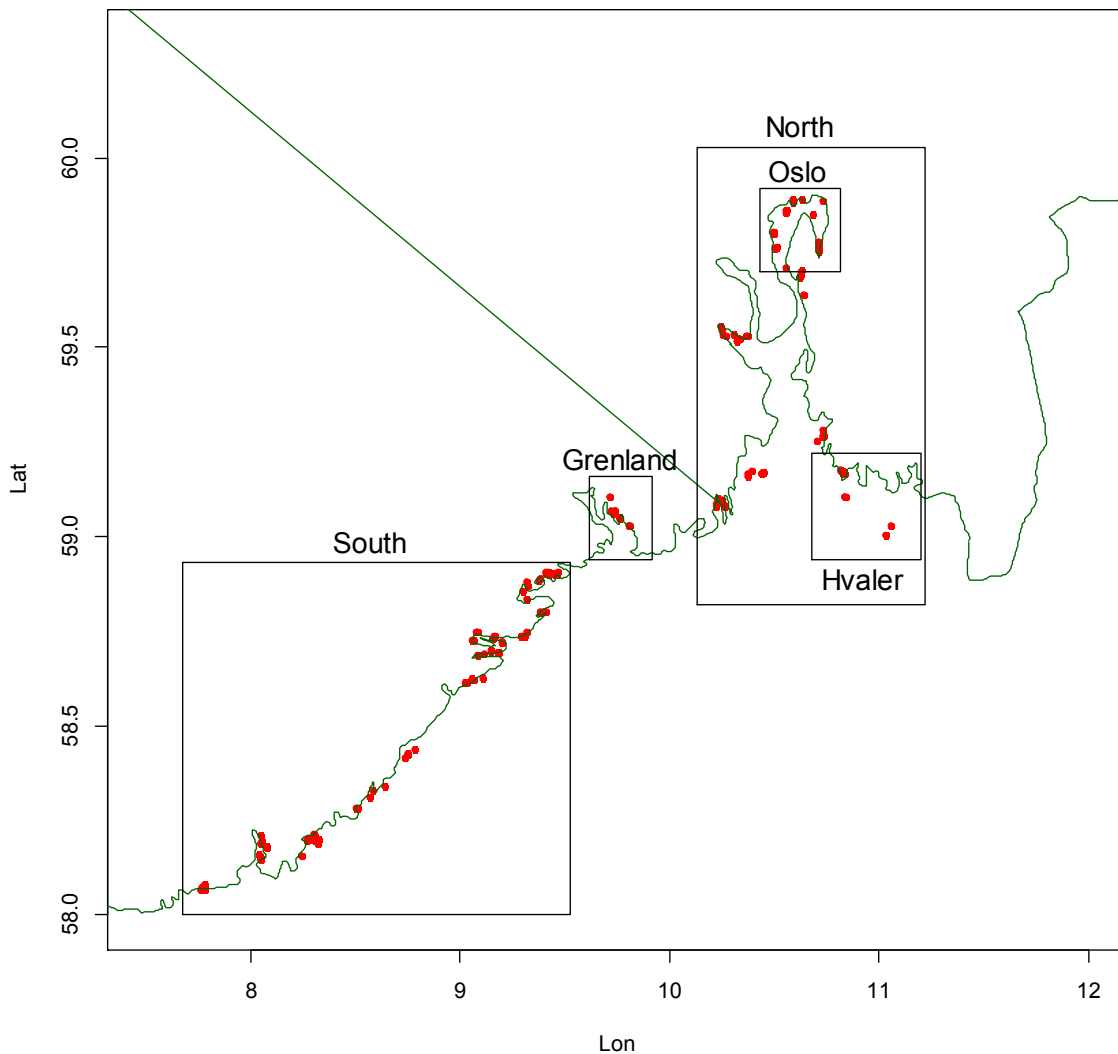


Figure 3. Regions used in the analysis. For the time series plots, North was taken as the stations exclusive of Oslo and Hvaler; for the time series analysis, North, Oslo and Hvaler were combined.

Here, we estimated all parameters (the b 's) using linear regression, except $s_{2,3}$ (survival from age 2 to 3) which we set equal to 0.4 (following Bjørnstad et al. 1999). The parameters were estimated for each station separately. Thus, b'_{i1} indicates how much recruitment (age 0 cod) depends on the size of the spawning stock, which in the results will be denoted as spawning stock biomass (SSB) for simplicity. The coefficients b_2 , b_3 etc. indicates how each environmental variable (temperature and wind) affects the number of age 0 cod.

Model selection (i.e. selection of the variables X_1, X_2, \dots) was done separately for each region (South, Grenland and North), using a meta-analysis of the results for each station. In the meta-analysis, we used a backward regression approach where we started with a model with all variables, then, for each variable, we collected the t-values (i.e., estimate/SE) for all stations of the region. We then tested whether the mean of the t-values were significantly different from zero (one-sided t-test). The variable with the highest p-value was then excluded, and the process was repeated until all variables had $P < 0.05$.

For the analysis of the effects of contamination, one would ideally use contaminant data for Atlantic cod. However, as the number of stations and years sampled for Atlantic cod contaminants is limited we used contaminants in blue mussel as a proxy for the level of contamination in the local environment. In order to investigate whether there are between-area and between-year effects of contamination load (as measured by blue mussel concentrations) and Atlantic cod abundance, we picked four areas where we had fairly long time series of both estimates of Atlantic cod abundance and measurements of blue mussel contaminant concentrations (Fig. 4). We analysed the possible effects of 8 contaminants separately: mercury (Hg), cadmium (Cd), copper (Cu), zink (Zn), HCH-A, HCB, BCP-52, and PCB-153. We used medians from each year/area (to avoid pseudoreplication), and analysed the data using linear regression with $\log(\text{median abundance of 0-year old cod})$ as the response variable and area (as a categorical variable) and median contaminant concentration as predictor variables. For model selection (for each contaminant), we used Akaike's Selection Criterion (AIC).

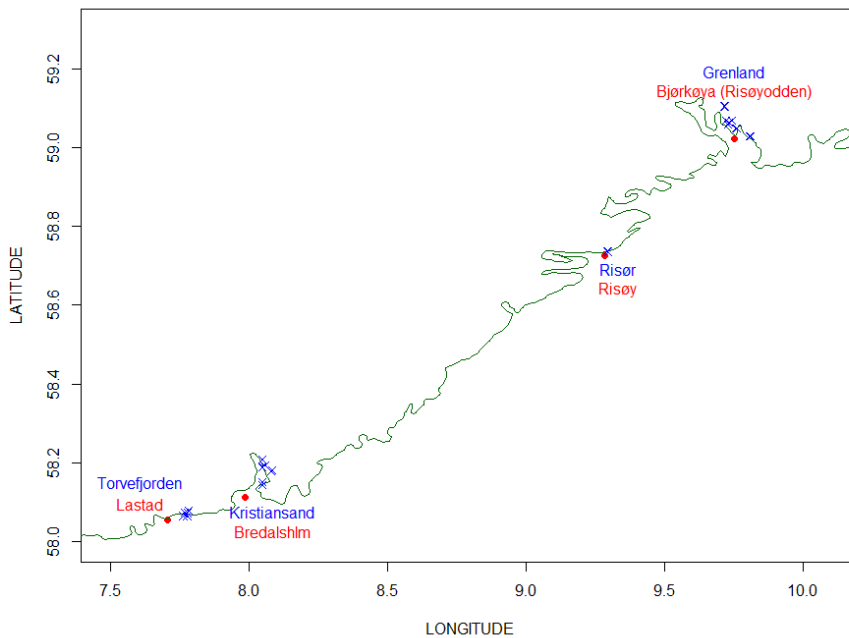


Figure 4. The four areas used to compare Atlantic cod abundance from beach seine surveys (blue crosses and print) to contaminant concentrations in blue mussels at MILKYS stations (red dots and print).

2.3 Results

2.3.1 Analysis of Atlantic cod time trends and effects of climate

In order to describe the historical and present abundance of young cod, we plotted the time trends (estimated by GAM) of the data, divided in five regions (Fig. 5). The three regions least affected by industrialization – South, North and Hvaler – all varied at about the same level. However, the temporal patterns were different: South and Hvaler peaked in the 1970s and decreased until ca. 1990 and has been stable since then, North peaked in the 1950s but has increased since 1980. The two presumably most polluted regions, Grenland and Oslo, have had lower abundance than the others since 1960 (Grenland appears to have had normal abundance until then). While the Grenland stock clearly appears to be recovering since 1980, the Oslofjord stock stays low.

The goal of the first time series analysis was to analyse the effect of climate variables on cod recruitment. Most of the climate variables showed trends over long time scales (Fig. 6). Of the local weather variables, τ_x decreased both in spring and autumn, indicating more on-shore and less offshore winds. τ_y (along-coast wind) showed overall increase (indicating less wind from the NE direction), but with little change after 1960. The temperature in spring has increased slightly (non-significantly), while autumn temperatures have increased significantly, especially since 1960.

The results of the model selection indicated that mostly the same variables were important for the southern and the northern regions (Tab. 1; note that the northern region here includes Oslo and Hvaler). In both regions, recruitment was high in years with off-shore wind in the spring (positive values of τ_x ; Fig. 7), along-shore wind from the NE in the autumn (positive values of τ_y), high temperatures in the spring, and low temperatures in the autumn. In addition, there was a strong effect of SSB (the estimated spawning stock biomass). In the northern region, the NAO-index was also important: years following high NAO winters (i.e. mild, windy winters) had lower recruitment. For the Grenland area, these variables did not enter the final model, with the exception of SSB (while along-shore wind in spring entered the model). However, this difference may well be caused by a much lower statistical power for Grenland, which has a low sample size (11 beach seine stations).

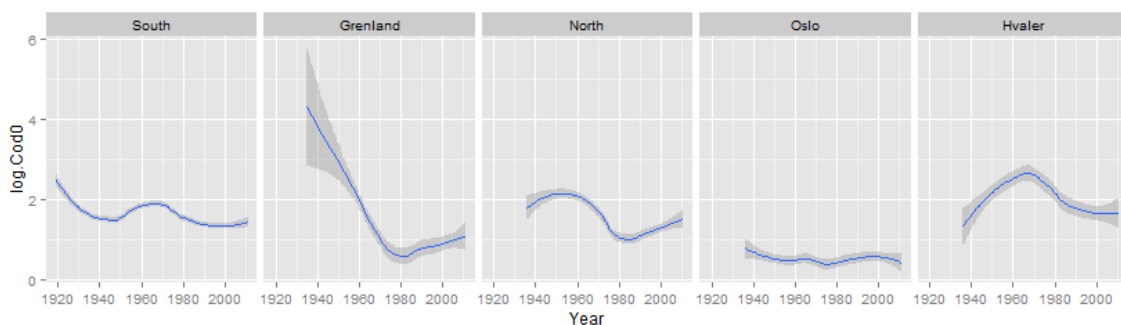


Figure 5. Time trends in abundance of 0-group Atlantic cod in five regions. The regions are defined as follows: South = south of Grenlandsfjord, Grenland = Grenlandsfjord, North = north of Grenlandsfjord except Oslo and Hvaler, Oslo = the inner part of Oslofjord, and Hvaler = Hvaler islands (close to the outlet of the major river Glomma).

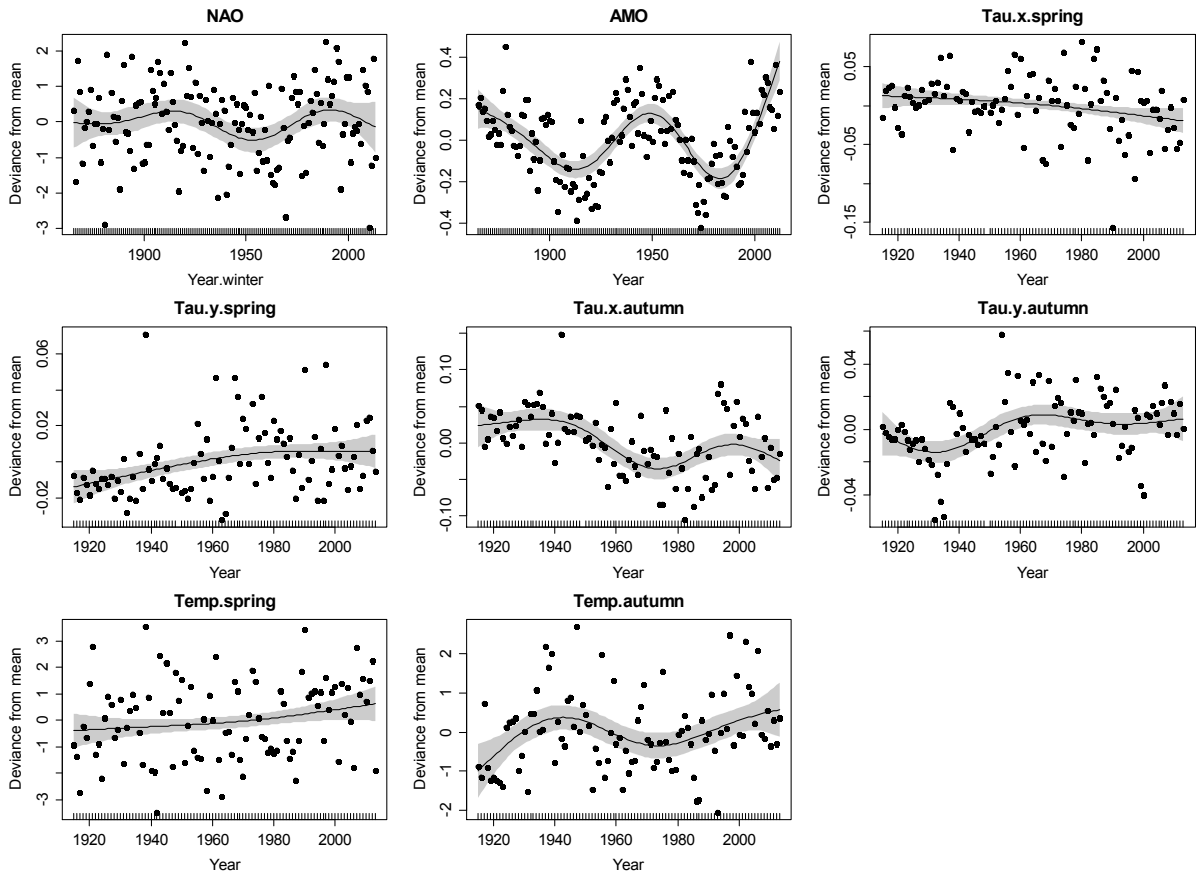


Figure 6. Time trends in the predictor variables: NAO (North Atlantic Oscillation), AMO (Atlantic Multidecadal Oscillation), Tau.x (wind strength perpendicular to the coast), Tau.y (wind strength along the coast) and Temp (air temperature). The last three variables were computed for both spring and autumn (see text). Time trends estimated by GAM are also shown; except NAO and Temp_{spring}, all trends were significant at the $P < 0.05$ level (Tau_{x,spring}) or the $P < 0.01$ level (all the rest). NAO ($P = 0.056$) and Temp_{spring} ($P = 0.075$) were near significance. The lower variance at the start of the wind time series (tau.x and tau.y) is an artefact of using regression to fill in missing values of Torungen data, using Færder data as a proxy.

Table 1. Final models after model selection for each region. The table shows p-values for a test that the t-values for all stations had a mean value significantly different from zero. A hyphen indicates that the variable was excluded from the model. Tau.x and Tau.y is the onshore an along-shore wind stress, respectively, and SSB.area is the effect of the previous spawning stock, i.e. b_{i1} in eq. 1 or b'_{i1} in eq. 2.

	<i>South</i> (<i>N=74</i>)	<i>Grenland</i> (<i>N=11</i>)	<i>North</i> (<i>N=55</i>)
NAO	-	-	0.0000
Tau.x.spring (onshore wind stress, spring)	0.0000	-	0.0003
Tau.y.spring (alongshore wind stress, spring)	-	0.0011	-
Tau.y.autumn (alongshore wind stress, autumn)	0.0001	-	0.0164
Temp.spring (air temperature, spring)	0.0000	-	0.0000
Temp.autumn (air temperature, autumn)	0.0000	-	0.0203
SSB (effect of spawning stock biomass)	0.0000	0.0006	0.0000

When we use the same model for all areas, coefficients can also be compared among areas using ANOVA (Fig.). If all areas are modelled using the optimal model for North, we find that the intercept ($P < 0.001$), NAO ($P = 0.02$), $\text{Temp}_{\text{spring}}$ ($P < 0.01$) and $\text{Temp}_{\text{autumn}}$ ($P < 0.001$) were significantly different among areas. The South region had stronger effects of NAOwinter, $\text{Temp}_{\text{autumn}}$ and $\text{Temp}_{\text{autumn}}$. The two latter variables had a significant effect for both South and North, but $\text{Temp}_{\text{spring}}$ had a stronger positive effect in North, while $\text{Temp}_{\text{autumn}}$ had a stronger negative effect in South. The Grenland region (between the vertical lines in Fig. 6) had significantly less effect of autumn temperature than the two other regions, and two of the three stations with highest effect of the spawning stock (SSB) were in the Grenland region.

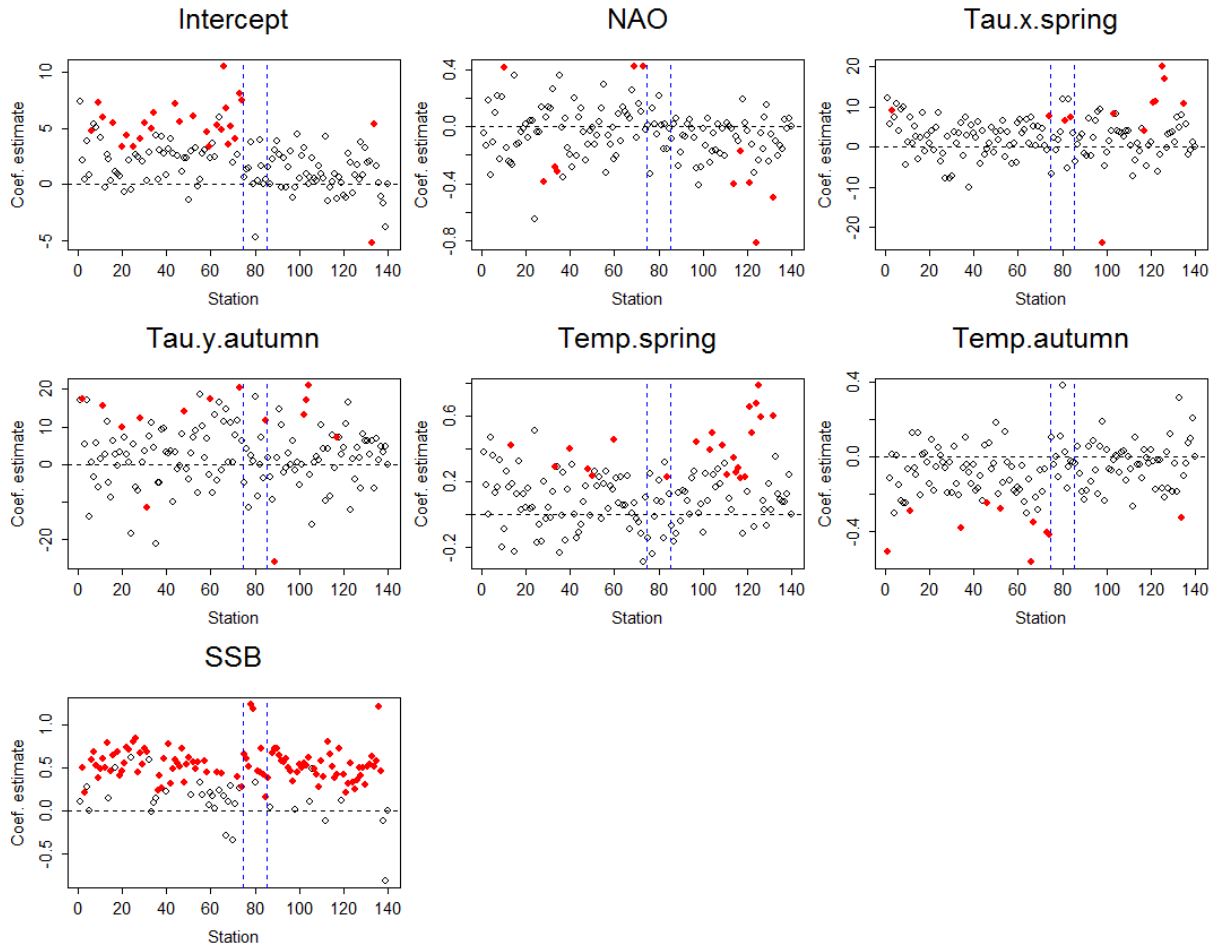


Figure 7. The optimal model for North applied to all stations. The graph shows estimates of each coefficient on Atlantic cod recruitment (y axis) on each station (x axis). The vertical dashed blue lines indicate the three regions South (to the left of the dashed lines), Greenland (between the dashed lines) and North (to the right of the lines). Red dots indicate cases where the variable was significant ($P < 0.05$) for the given station in isolation. Variable names are explained in Fig. 6, except SSB, which is the effect of the size of the spawning stock (b'_{it} in eq. 2).

2.3.2 Effects of contamination

All stations with at least three years of data on contamination in Atlantic cod are shown in Fig. 8. These data were not used in the analysis, but a plot of these data (Fig. 9) confirms the general high level of contamination in the Oslo area. The concentrations in blue mussel (Fig. 10, 11) were used as a proxy in the analysis of contamination load and cod abundance in four areas (Fig. 4). A statistical analysis showed that for three of the eight contaminants (HCH-A, HCB, and PCB-153), the model with both contaminant concentration and area (as a categorical variable) was the optimal model according to the AIC criterion (Tab. 2). As expected, the effect of concentrations was negative in all cases, although the effect was apparently weak and variable (Fig. 12). Thus, contaminant concentrations appear to have an explanatory effect on Atlantic cod abundance when the general difference in Atlantic cod among areas had been taken into account.

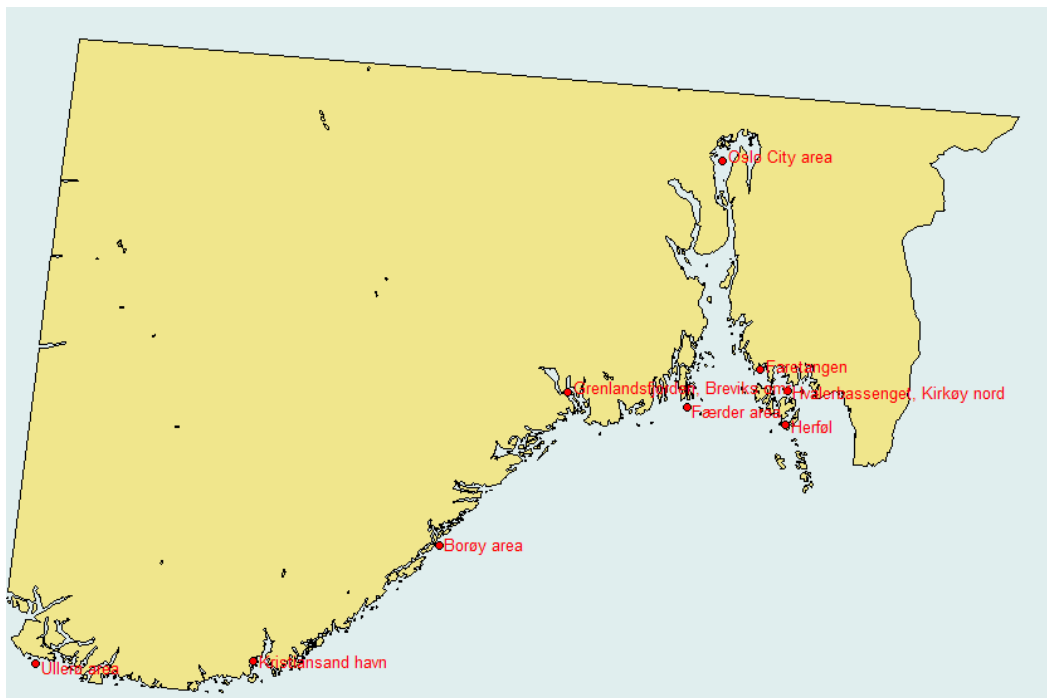


Figure 8. Stations with at least three years of data on contaminants in Atlantic cod in the MILKYS programme.

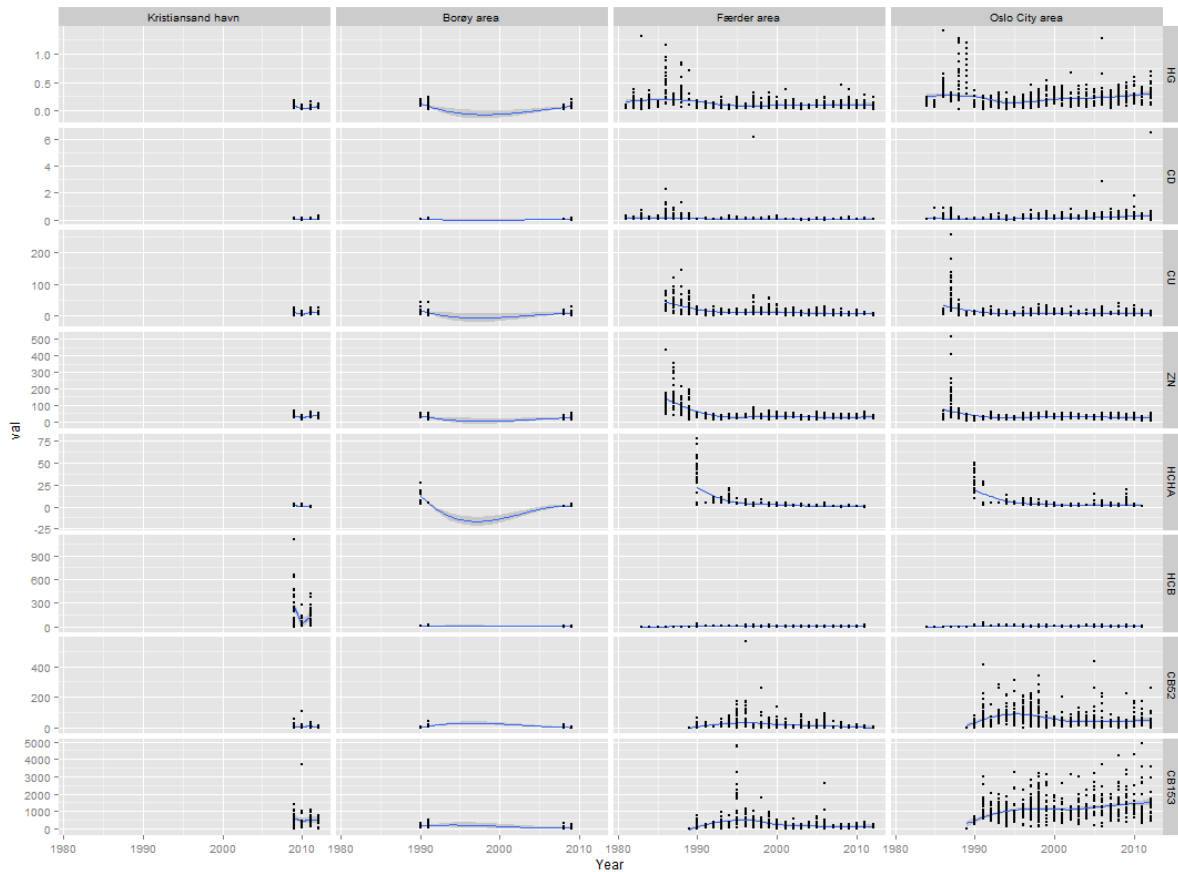


Figure 9. Time series of selected contaminants (Hg, Cd, Cu, Zn, HCH-A, HCB, PCB-52, PCB-153) in Atlantic cod muscle (for Hg) or Atlantic cod liver (all other contaminants).

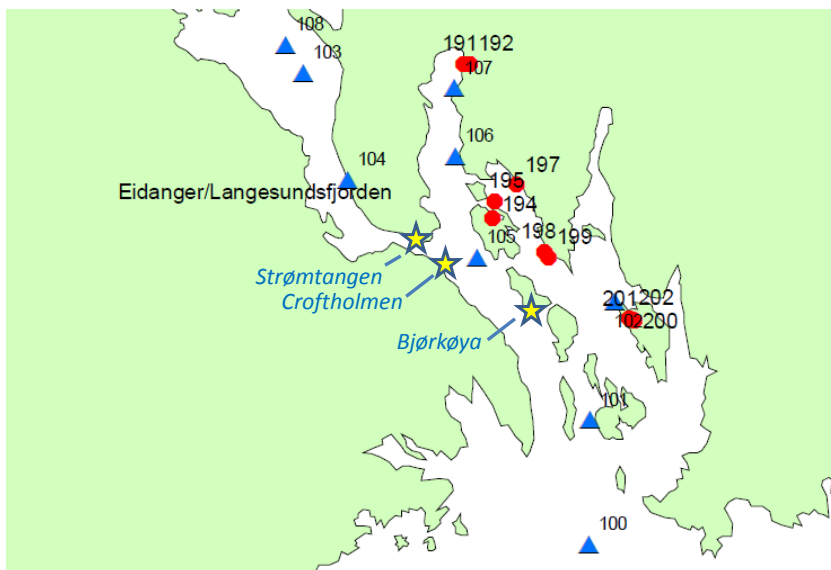


Figure 10. Map of the Grenland area with the present stations in the Atlantic cod beach seine survey (red dots, numbers) and stations for sampling contaminants from blue mussels in the MILKYS program (stars). Blue triangles represent hydrographical stations (not used in this study).

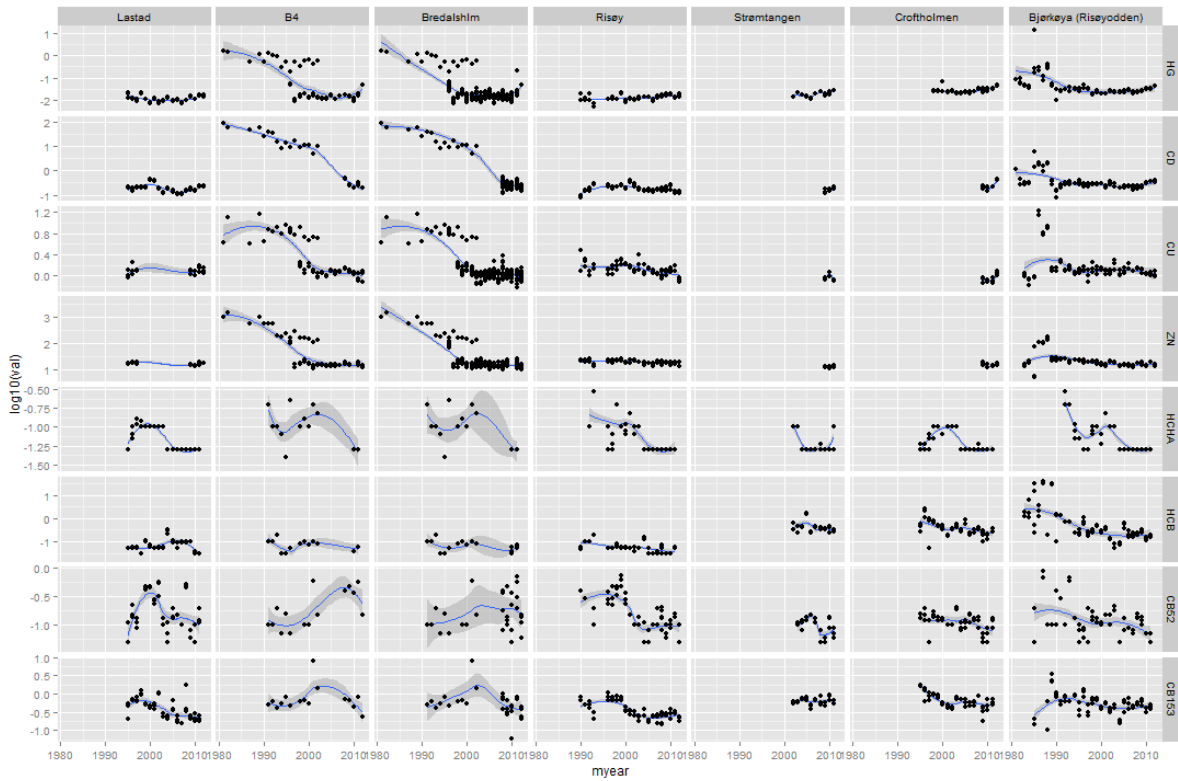


Figure 11. Time trends of selected contaminants in blue mussel in selected sites (see maps in App. B)

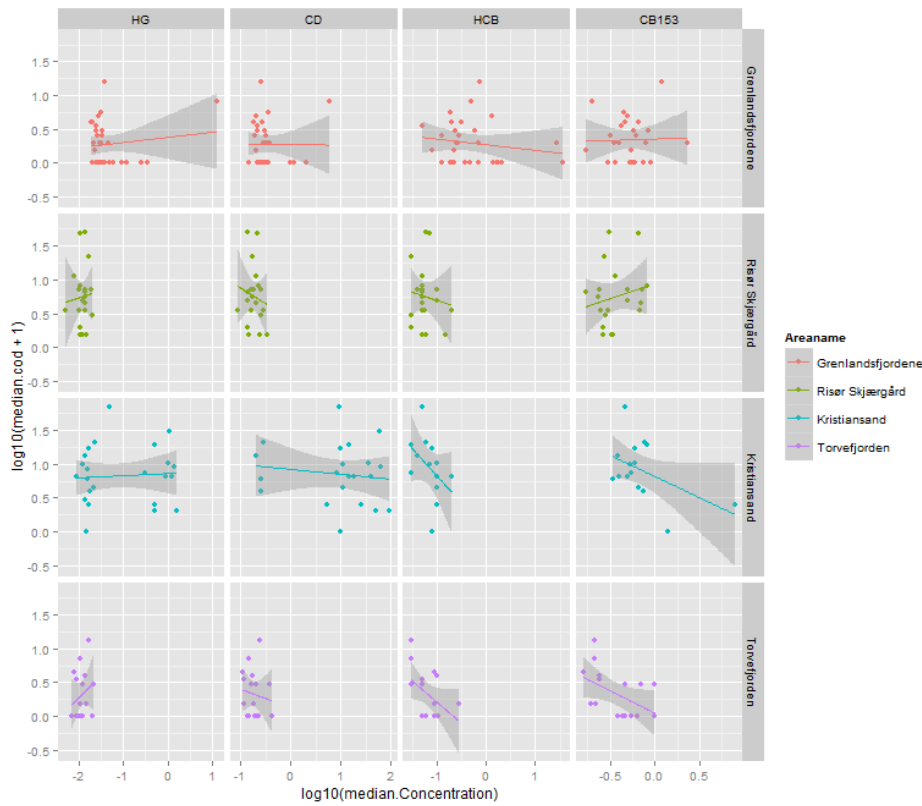


Figure 12. Abundance of Atlantic cod (y axis) relative to concentrations of four contaminants in blue mussel in four areas (see Fig. 4). CB153 = PCB-153. Two of the contaminants (HCB and PCB-153) had a statistical effect on cod abundance.

Table 2. Models for explaining Atlantic cod abundance in 4 areas, as a function of area, concentration of contaminants in blue mussels, or both. The model parsimony (the fit with a punishment for the number of variables) is shown using the model's dAIC values (the difference between AIC and the minimum AIC). For each row, the optimal model has dAIC = 0 (shown in bold). Lower dAIC values indicate the more parsimonious model. A zero in the "Concentration + Area" column indicates that the model taking into account both area and concentration of contaminants was the best model.

	Concentration	Area	Concentration + Area
Hg	29.71	0.00	1.41
Cd	24.81	0.00	1.34
Cu	18.37	0.00	1.05
Zn	18.95	0.00	2.00
HCH-A	22.63	0.40	0.00
HCB	16.87	0.84	0.00
PCB-52	21.40	0.00	0.53
PCB-153	23.97	0.32	0.00

2.4 Discussion

The data indicate clear effects of both climate variation and pollution on the abundance levels of 0-group fish. The clear regional differences apparent in the data are consistent with a strong effect of pollution on the regional abundance, as the recent numbers of Atlantic cod juveniles in Grenland and inner Oslofjord are far lower than in other areas. For Grenland, the decline of Atlantic cod juveniles from over-average abundance to the lowest levels along the coast is striking and it is hard to find a more likely explanation than the heavy industrialization, in particular the start of the magnesium plant in 1951. The inner Oslofjord, however, differs from other areas not only by being polluted, but also by being quite closed and relatively isolated from the Skagerrak area. Thus, it may have lower recruitment of Atlantic cod due to its oceanographic conditions. Also, counts of Atlantic cod eggs along the coast have recently shown the highest levels in the inner Oslofjord (Sigurd Espeland, pers.comm.).

In areas less affected by contamination, we find strong effects of both wind and temperature. Temperature had opposite effects in spring and autumn: a high spring temperature was positive, while a high autumn temperature was negative. This agrees qualitatively with Rogers et al. (2011), who got basically the same result with respect to length of Atlantic cod juveniles. A positive correlation with spring temperature – possibly related to the abundance and/or timing of the spring bloom - has been documented for many Atlantic cod stocks in the northern range of Atlantic cod (Dutil & Brander 2003). Consistent with this, we found a stronger positive effect of temperature in the northern range of the area. Interestingly, this was coupled with a negative effect of NAO in the northern area, i.e., the ideal spring is a cold winter followed by a warm spring. For the summer temperature, optimal growth in Atlantic cod occurs at 12-15 °C (Björnsson et al. 2001), while higher temperatures may have a metabolic cost. One important mechanism may be that high temperatures increases the fish' demand for oxygen and decreases the water's oxygen concentrations (Pörtner et al. 2001). We found a stronger negative effect of summer temperature in the southern range of the area, which again is consistent with expectations.

For wind we found a positive effect of wind in the off-shore direction in the spring, and along-shore wind from the NE in the autumn. Off-shore wind leads to upwelling, which may contribute to intensifying or prolonging the spring bloom, thereby increasing the availability of food for the Atlantic cod larvae in the early critical period. There is genetic evidence that some of the cod juveniles found in the coastal beach seine surveys in fact are individuals are not of local origin, but are juveniles from the North Sea population of cod (Knutsen et al. 2004). A later study (Stenseth et al. 2006) also found evidence that the abundance of North Sea cod juveniles could be linked to oceanographic conditions favouring such a transport by currents in spring. We have not tried to investigate whether off-shore wind could be favouring such transport (e.g., if the wind drags surface waters out of the fjord, this may cause deeper waters to move into the fjord). However, Stenseth et al. (2006) estimated that only a moderate amount of the total 0-group populations (on average, 1–10%) come from the North Sea, which probably is too little to explain the large variation in the data. For the autumn wind conditions, along-shore wind from the NE tends to lead to accumulation of water along the coast by Ekman transport (Mann & Lazier 2006). Since the autumn period overlaps the period of sampling, we cannot rule out that these wind conditions leads to more efficient sampling of the beach seine, simply because more larvae are concentrated close to the coast. Thus, we cannot exclude that autumn wind condition affects sampling efficiency rather than the actual abundance of Atlantic cod juveniles.

In the analysis focused on Atlantic cod abundance and pollution levels, we found that year-specific levels of some contaminants – measured in blue mussels - helped explaining variations in Atlantic cod juvenile abundance. Also other contaminants tended towards having a negative effect, but only three contaminants – HCH-A, HCB and PCB-153 - did improve the explanatory power statistically. One should be somewhat cautious interpreting this result, as there

are time trends in both Atlantic cod and contaminant time series.

It should be emphasized that variation in the abundance of adult cod is also to a large extent affected by variation in survival after the juvenile stage, which we have not considered here. An analysis also including catches of 1- and 2-year old cod in trammel nets (at 3 sites in a limited number of years since 1985) indicates that survival after the juvenile stage has declined in the eastern parts of Skagerrak (Gjørøseter & Danielssen 2004). Our analysis, by only considering variation in cod juveniles, is best viewed as a study of recruitment (which takes into account the expected autocorrelation due to the effects of spawner abundance), which also may play some role in the variation of adult fish.

2.5 Additional data and alternative methods

Due to time limitations, there exist other sources of data that we could have used (1) Analysis of data for cod older than 0 year. The beach seine catch less of these age groups and the data are therefore even more affected by random variations. However, as survival between age 0 and age 1 may be an important determinant of the abundance of adult cod (Gjørøseter & Danielssen 2004) this should be part of an extended analysis.

(2) Use of cod length data. Cod length is often correlated with abundance and may give important information on the stock's well-being-. Also, it may be possible to use to separate local and North Sea cod.

(3) Harvesting data. Data on landings of cod by municipality, month and year back exist to 1977. We did not put high priority to these data as they have the following issues: (1) the data covers a limited period compared to the beach seine data; (2) fish may often not be landed in the closest possible municipality; (3) the data is not immediately usable, for instance, one has to deal with changes in the municipality structure since 1977; and (4) the total amount of fished cod may be quite different from the data, as the data does not include hobby fisheries, which can be quite substantial in this area. For the last point, Svedäng and Bardon (2003) found that informal statistics such as records of sport fishing clubs and notes they got from local fishermen were more informative as official logbook data. We presume that these are reasons that cod landings data has not been used in earlier studies of these cod populations. However, it would be interesting to use it in later analyses.

(4) Analysis of contaminant data other than the MILKYS database, in particular data on dioxins and other contaminants from the Grenland fjords (from "Statlig program for forurensingsovervåking").

(5) Analyses of data on the physiological condition of individual fish, both weight relative to length (condition) as well as liver and gonad weight relative to total weight (the hepatosomatic index and the gonatosomatic index, respectively). Such data exist both in samples taken by the Institute for Marine Research, and in the databases from contaminant-focused programs.

(6) Data on benthic vegetation and fauna exist for stations in this area for the period 1990-2010 (Kystovervåkingsprogrammet). As the bottom habitat is a critical habitat for young cod, this could be an important factor for the cod stock's well-being. The existing data does indicate negative trends in the diversity of benthic organisms since the mid-1990s, and that high density of particles and extreme temperatures has a negative effect on benthic diversity.

(7) Data on predators such as cormorants and seal. It is not known whether time series of abundance or abundance indices of these predators exist. Even if only estimates of abundance and consumption (not time series) exist, one may use these data to find the possible effect on cod populations.

(8) Data on zooplankton (specifically, copepods), which are important food for the Atlantic cod during its early life stages, are collected by IMR and may explain some variation in recruitment

(9) Capture-mark-recapture data on cod exists at IMR; we did not ask to use these data.

In order to extract information on Atlantic cod dynamics using data from only one point in the life cycle, the preferable method is a state-space model, where one can insert information on the Atlantic cod's life cycle, and differentiate between measurement errors (due to noise in the sampling) and process errors (which reflects actual unexplained variation in the population). This also has the advantage that the method handles gaps in the time series. This has previously been done by Bjørnstad (1999); however, he aggregated the data for large parts of the coastline, while we wanted a finer spatial resolution. On the station level, also the 0-group data are very noisy, with many zeros and being best described by a negative-binomial distribution. By using JAGS (<http://mcmc-jags.sourceforge.net/>), we were able to construct such a state-space model which was able to robustly estimate the model parameters for simulated data, even when these data contained very high levels of noise. However, we were not able to make the method converge for real data when we used data on the station level.

2.6 Advice for the management

One can use several approaches to study which factors that affect natural populations: statistical analyses of observational time series (such as this study), experimental studies in the field (where the natural conditions are manipulated in some way), experimental studies on animals in the lab, physiological studies of the effect of contaminants on animals, studies of diet of the study species and the predators of the study species, etc. Substantial advances in the knowledge of natural systems often results from a *combination* of such approaches. For instance, statistical analyses of observational time series are by nature correlative and cannot be used as conclusive proof of cause and effect. However, they can (typically) cover a much larger period of time and a larger area than more intensive, costly studies (e.g., analyses of diet, or field experiments). Also, they can generate hypotheses which later can be tested in the lab or by other labour-intensive efforts. For instance, a statistical study may indicate that fish are affected by an interaction between two factors, while experimental studies in the lab (on e.g., the effect of contaminants) typically are designed for testing one factor at a time.

Our advice to increase the understanding of the Atlantic cod in the Skagerrak region are listed below.

- (1) Time series
 - a. The established time series of the area, including the beach seine survey and MILKYS, should be continued
 - b. One should be conservative regarding methodology, position and time of the year of the sampling; i.e., one should have very good reasons to change any of this.
 - c. If methodology, position and time of the year is changed, the value of the time series increases a lot if one has one or (preferably) a few years with overlap, i.e. where both the old and the new method/position/time is used
 - d. The termination of the annual benthic surveys after 2010 is unfortunate, as young cod depends on suitable benthic habitat, and changes/trends in the structure and diversity of the benthic community may be important
- (2) In recent years, IMR has performed tagging-recapture of adult cod through externally funded projects for a limited time. These studies have proved to give a lot of information on the development of fishing mortality, adult population size and movement. Given the state of the cod stocks, tagging-recapture of cod should be given high priority and should be given more stable funding (e.g., as part of a monitoring program)
- (3) While the coastal current is well monitored, knowledge of the dynamics of the physical environment and primary production inside fjords is limited. A system of loggers for inside some fjords would be very valuable, also for monitoring/studies on other species (salmon and trout, sugar kelp). Loggers should record at least temperature and salinity, preferably also oxygen concentrations, chlorophyll A and chromophoric dissolved organic matter (CDOM, which can alter alters availability of contaminants and nutrients)
- (4) Knowledge of contaminants in cod food items, especially shrimps, is needed for more areas (this has been measured in Grenland)
- (5) Lab studies under realistic conditions (temperature, food availability) can be used to confirm (or reject) hypotheses about, e.g., effects of contaminants under a range of temperatures and availability of food
- (6) Focused observational field studies can be used for questions which are not easily studied in the lab, for instance the importance of bottom habitat for cod (e.g., by counting cod in different types of habitat) and the importance of cod in the diet of predators (e.g. cormorants, seal)
- (7) Analysis
 - a. Researchers should be encouraged (i.e., given enough time/money) to analyse the available data
 - b. Researchers/institutions who collects data should be given incentives to share data/knowledge

3. Black-legged kittiwake on the Norwegian coast

3.1 Data

The fate of a seabird colony is determined by reproduction (number of eggs per adult), survival of chicks until fledging, and the annual survival thereafter. For black-legged kittiwakes in Norway, data on the number of eggs per adult and the survival of chicks has been collected for several years, together with data on colony size as well as estimates of adult survival (from capture-mark-recapture studies). The survival of subadults (between fledging and first breeding) is more difficult to estimate, but then one can in principle determine this from the other data, based on the other measurements and the population development of the colony. Additional data that is useful includes samples of food brought back to the nest. Thereby, one may link the state of the environment (sea temperature, abundance of key fish species) to the kittiwake's diet, which may be correlated with chick survival, and finally one may model how variations in chick survival affects the development of the colony.

Unfortunately, we did not have access to all existing data for black-legged kittiwakes for this project. The program for seabird monitoring, Seapop (www.seapop.no) has collected detailed population data for a number of seabird colonies for several years, including counts nests and chicks in colonies, capture-mark-recapture data and data on feeding during the breeding season. The program has also several time series established long before the start of the Seapop program. Here, we make use of the part of the data made publicly available.

3.1.1 Breeding numbers at the Runde and Skrova colonies

This is two of the longest abundance time series of black-legged kittiwake in Norway. They are published as indices (breeding numbers as per cent of breeding numbers in 1980) on the web page of Environmental Status of Norway (<http://www.miljostatus.no/indikatorer-Norskehavet#Sjofugl>). From additional information we have found the absolute numbers of the Skrova time series and approximate absolute numbers for Runde.

3.1.2 Adult survival and breeding success for surveyed colonies

These data were only available for a few years, taken from Seapop reports.

3.1.3 Data on contaminants in seabirds and fish

Data on contaminants in seabirds exist for some years and locations, mostly for black-legged kittiwakes outside mainland Norway (Bjørnøya and Svalbard). Only metadata will be presented here. Data on contaminants in fish can be downloaded from the National Institute of Nutrition and Seafood Research (NIFES, <http://www.nifes.no/sjomatdata>).

3.2 Methods

Due to the limited data available, we formulated a simple population model to analyse how different factors may affect the black-legged kittiwake populations. The model is a very simplified version of the kittiwake's life history. The model follows the number of kittiwakes by age, including chicks (counted as 0 year old birds). First, we assume that all kittiwakes over a certain age (*Amat*) breed, and that each black-legged kittiwake pair lays 2 eggs. Each chick survives until fledging with a certain probability (chick survival S_{chick}). The adults survive from one breeding season to the next with a probability S_{adult} (adult survival). For simplicity, we assume that subadult survival (for each year from the fledging stage until their first breeding) is equal to adult survival (this will be discussed later). Thus, we consider only two mortality parameters: chick mortality (from egg laying to fledging) and subadult/adult mortality (here after just denoted adult mortality for simplicity).

First, let us assume chick and adult mortality is constant, and ignore environmental and demographic stochasticity. We can set up the following simple model:

$$N_{0,t} = N_{mat,t} E S_{chick} \quad (\text{eq. 3a})$$

$$N_{a,t} = N_{a-1,t-1} S_{adult} \quad (\text{eq. 3b})$$

$$N_{mat,t} = \sum_{a=Amat}^A N_{a,t} \quad (\text{eq. 3c})$$

where $N_{0,t}$ is the number of fledglings in year t , $N_{mat,t}$ is the number of mature (breeding) birds, $N_{a,t}$ is the number of birds age a in year t , and $Amat$ is the age at first breeding. E is the number of eggs per adult, S_{chick} and S_{adult} is, respectively, survival of chicks mortality and the annual survival after the chick stage. Note that N here refers to individuals, so because we assume two chicks per nest, E is 1. (Numbers of seabirds in a colony is usually given as the number of pairs.) Also note that this equation is still valid if breeding birds permanently leaves the colony (i.e., goes to a different breeding site when they return from the winter feeding range). If one simulates this model over a long time, the age distribution (the percentage of $N_{0,t}$, $N_{a,t}$ etc. of the total sum of $N_{0,t}$) becomes constant, as does the growth rate r_t , which we here define as the annual rate of change of breeders:

$$r_t = \log_e \left(\frac{N_{mat,t+1}}{N_{mat,t}} \right) \quad (\text{eq. 4})$$

Thus, when the age distribution has become constant, r_t converges towards a constant, r , which depends only on S_{chick} , S_{adult} and $Amat$. In our simulations, we assumed that all black-legged kittiwakes breed from age 4 years (Strøm 2013), although this is also a parameter that may vary with environmental parameters.

Based on this simple model, we introduce some realism by letting the survival parameters vary between years due to variation in food abundance etc. (*environmental stochasticity*). Thus, we let S_{chick} and S_{adult} vary over time:

$$S_{chick,t} = \overline{S_{chick}} + \varepsilon_{chick,t} \quad (\text{eq. 5a})$$

$$S_{adult,t} = \overline{S_{adult}} + \varepsilon_{adult,t} \quad (\text{eq. 5b})$$

where $\overline{S_{chick}}$ and $\overline{S_{adult}}$ is the mean survival over time, and $\varepsilon_{chick,t}$ and $\varepsilon_{adult,t}$ is random variation (to ensure that M stays between 0 and 1, M was logit-transformed, normally distributed random variation was added, and then the result was back-transformed). Then the growth rate r_t will over time converge towards a constant distribution which varies over time around the mean \bar{r} . This mean depends not only on the means $\overline{S_{chick}}$ and $\overline{S_{adult}}$, but also on the degree of variation around the means.

Finally, black-legged kittiwake populations are often small, and we cannot ignore *demographic stochasticity*, e.g., variation solely due to small numbers. For instance, a higher fraction than $S_{adult,t}$ of the adults may die between seasons simply due to bad luck. If the death of each adult is independent of each other, the probability that each adult will survive between breeding seasons is $S_{adult,t}$, and the number of surviving adults will be Poisson-distributed. If we make the same assumption for chick survival, we can rewrite eq. 3a and 3b as

$$N_{0,t} = \text{Poisson}(N_{mat,t} S_{chick,t}) \quad (\text{eq. 6a})$$

$$N_{a,t} = \text{Poisson}(N_{a-1,t-1} S_{adult,t}) \quad (\text{eq. 6b})$$

We ran simulations and calculated the resulting r with all three scenarios: without stochasticity (eq. 3), with environmental stochasticity (eq. 5) and with environmental and demographic stochasticity (eq. 7). In all cases, we started the simulations using the stable age distribution (found by simulating the population for 50 years using eq. 3).

3.3 Results

3.3.1 Population modelling

Both the Runde and Sklinna populations have decreased dramatically since 1980, and in Sklinna, no birds bred since 2010 (Fig. 13). The data in the Seapop reports indicates that chick survival decreases from north to south (Fig. 14), while adult survival (and fidelity to the breeding location) is similar across sites (where this has been estimated) with a mean of 83-85% (Fig. 15). Also, year-to-year differences in chick survival is very high, with a high probability of zero or close to zero chicks that are successfully reared to the

In the case of the deterministic simulation of the model, an adult survival of 83-85% means that a mean chick survival of ca. 0.3 is needed in order to keep the population from declining (Fig. 16a). To be precise, if the adult survival is 84%, the population will be stable with a chick survival of 32% (assuming that the birds all start to breed at age 4).

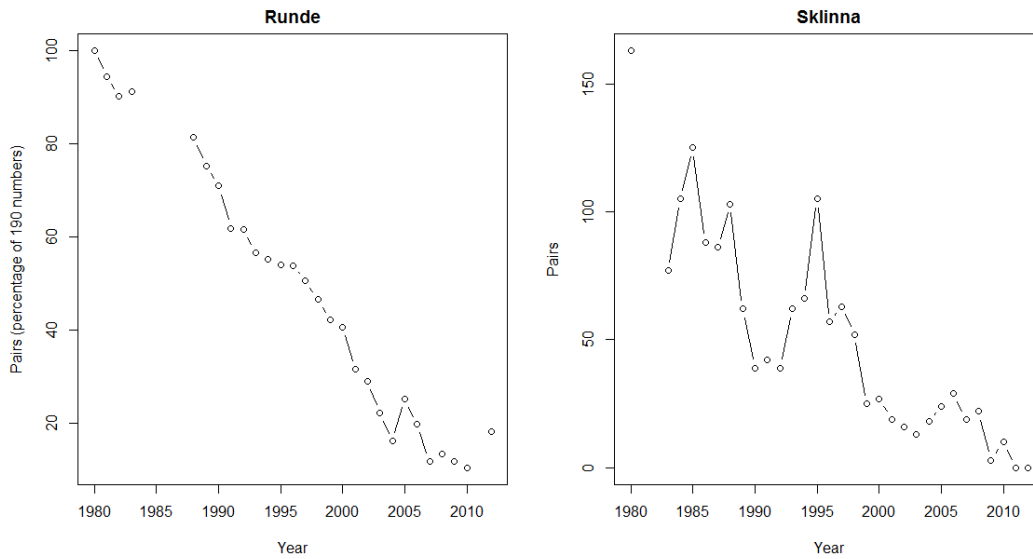


Figure 13. Time series of the number of breeding black-legged kittiwakes at (a) Runde and (b) Sklinna. In the case of (a) population size is given as percentage of population size in 1980 while (b) gives the real population size. The population sizes at Runde are much larger than the sizes at Sklinna (on the order of 50000 pairs in 1980).

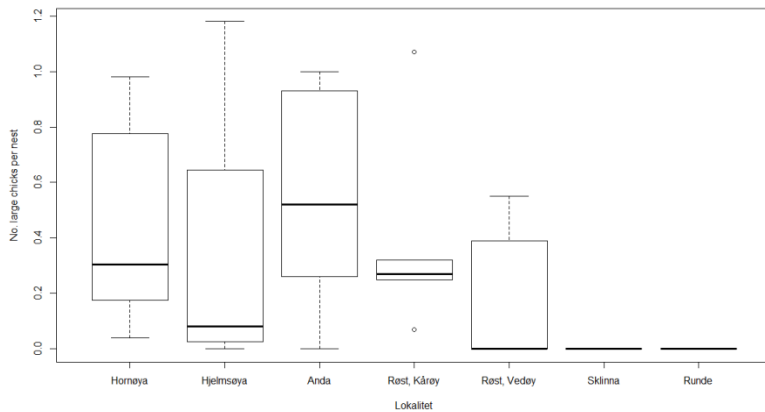


Figure 14. Number of large chicks per nest in the Seapop studies. This is taken to be $2 \times (\text{chick survival rates})$ in our model. Colonies are order from North to South.

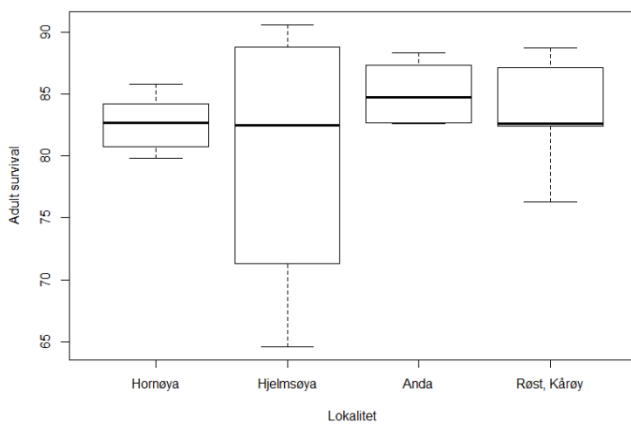


Figure 15. Adult survival in the Seapop studies. Note that some of the rates are survival rates calculated from one year to the next, while other rates are calculated over several years (the latter are therefore expected to have a lower variation than the year-to-year variation). Colonies are order from North to South.

If we added realistic values of environmental stochasticity (year-to-year variation in chick and adult survival, i.e. eq. 5), the viability of population with mean adult survival is 84% will not change much. However, the inclusion of environmental stochasticity led to a population that was much more dependent on adult survival than on chick survival (Fig. 16b). That is, a small decrease in adult survival is difficult to compensate by increased chick survival: a decrease of adult survival of 6-7% would change a stable population into a population with and $r = -0.1$, or approximately 10% decrease per year. If we vary environmental stochasticity in adult and chick survival, we find that variation in adult survival is not likely to change the shape of the relationship between survival and r , but increasing variation in adult survival may change a stable population into a weakly decreasing one (Fig. 17a). In contrast, variation in chick survival changes the shape of the relationship between r and the two survival parameters: the higher variation in chick survival, the more the population depends on mean adult survival (Fig. 17b). If mean chick survival is low, increasing variance in chick survival may in fact increase the population's viability.

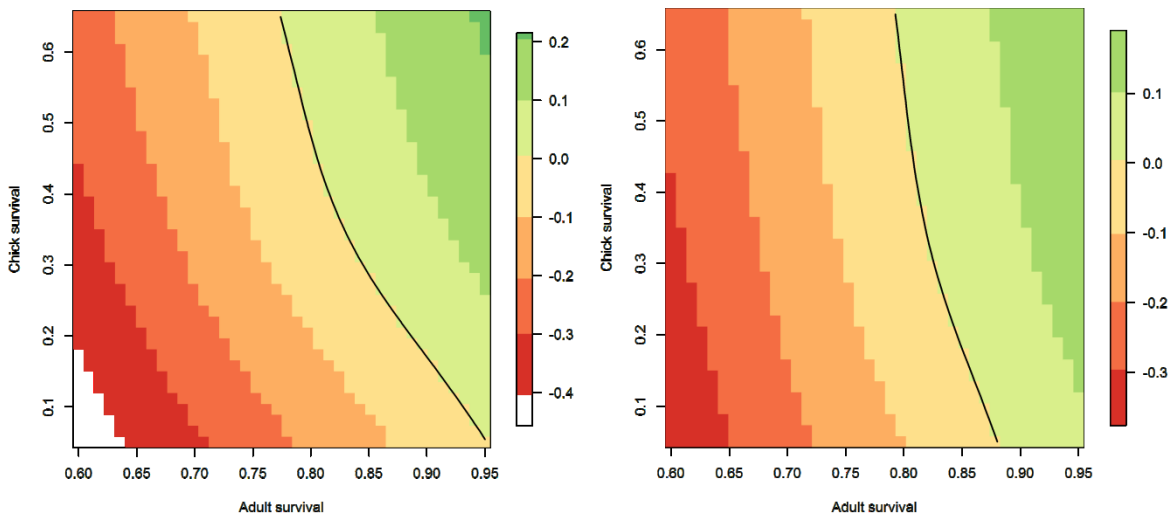


Figure 16. Population growth r as a function of adult survival (S_{adult}) and chick survival (S_{chick}) in the black-legged kittiwake population model. (a) Without environmental and demographic stochasticity (eq. 3), (b) with environmental (but not demographic) stochasticity (eq. 5). In both cases, we assumed maturation at age 4. The black line indicates $r = 0$, i.e. that the population is stable. The magnitude of environmental stochasticity was $\text{st.dev.} = 0.2$ and $\text{st.dev.} = 3$ on the logit-transformed adult and chick survival, respectively. This means that if mean chick survival is 84%, it is lower than 80.3% or higher than 87.2% in half of the years. For chick survival, it means that if mean chick survival is 30%, it is lower than 5% or higher than 76% in half of the years.

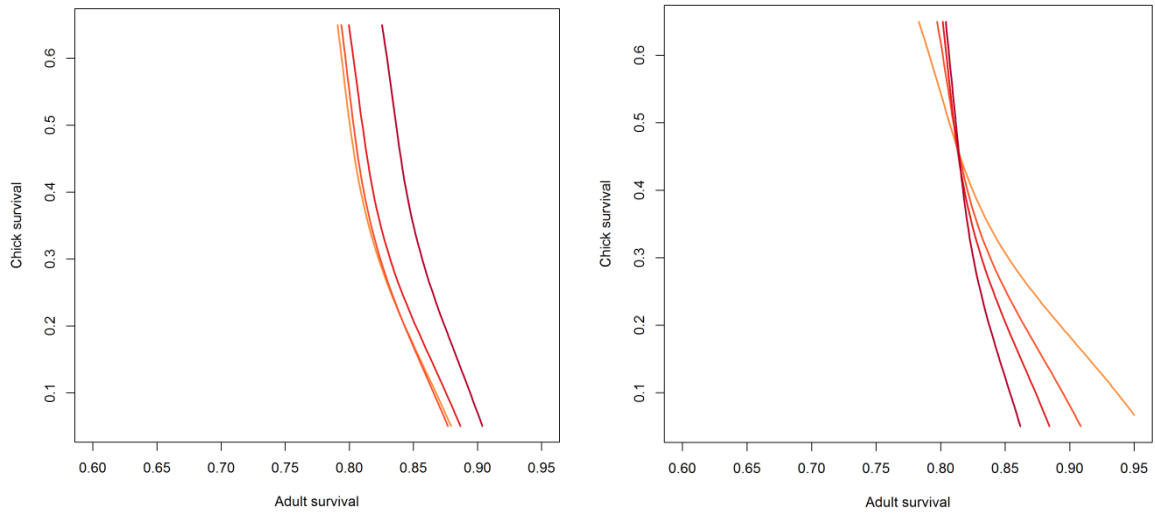


Figure 17. Contour lines for a stable population ($r = 0$) as a function of adult survival (S_{adult}) and chick survival (S_{chick}), for different levels of year-to-year variation in adult survival (a) and chick survival (b). The population will decrease to the left of the line. In (a), the variation in chick survival is as in Fig. 16b, while the variation in adult survival is changed from zero (orange line) to the double of Fig. 16b (dark red line). In (b) the variation in adult survival is as in Fig. 16b, while the variation in chick survival is changed from zero (orange line) to the double of Fig. 16b (dark red line).

To combine the results of the modelling with data from actual populations, we plotted the mean and the standard deviation of the growth rate for both the models and for the two populations with data (Fig. 18). If we trust the model's assumptions, the observed growth rate of the Røst and Sklinna colonies means that either mean adult survival rate is 80% (red dots in the figure), i.e., substantially lower than the survival rate observed in the more northerly colonies (c. 84%), or adult survival rate is as it is in the northerly colonies (84%, green dots) but there is an extremely low survival of chicken (5%, with little variation between years). The observed variability of the growth rate at Runde is in line with the variability predicted by a model with demographic stochasticity, which is as expected since the Runde population (even after drastic reduction) is still so large that we expect little effect of demographic stochasticity. For Sklinna, the observed variability of the growth rate is clearly very high compared to model results, indicating a very important role of demographic stochasticity.

The results indicate that demographic stochasticity reduces the mean viability of the population (Fig. 19). In addition, the variability among populations increase, so the probability of each population to go extinct increases.

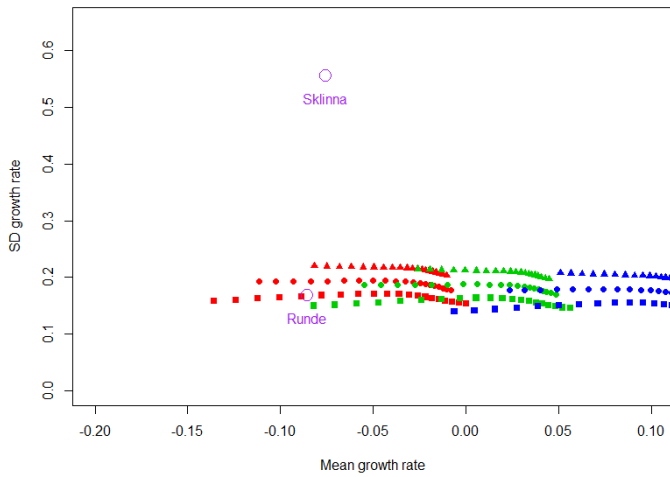


Figure 18. Comparison between the mean and variability (SD) of the growth rate (mean = x axis, SD = y axis) at Runde and Skinna with model results (including environmental, but not demographic, stochasticity). The three colors indicates adult survival of 0.80 (red), 0.84 (green) and 0.90 (blue). The three point shapes indicate low, medium and high variability of chicken survival (squares, circles and triangles, respectively). For each colour/shape, the leftmost points are for low mean chicken survival (5%) and the rightmost points are for high mean chicken survival (65%).

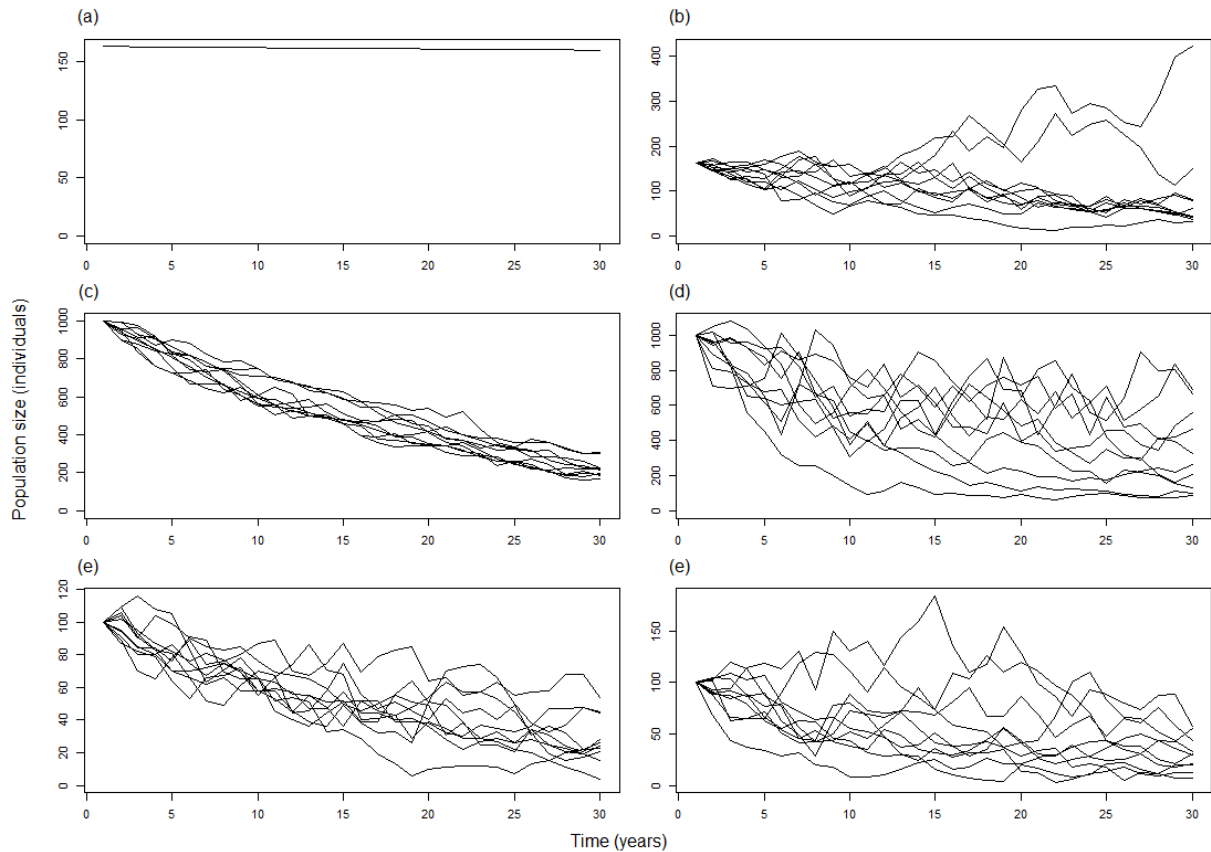


Figure 19. Effects of environmental and demographic stochasticity. In all cases, mean adult survival is 0.84 and mean chick survival is 0.32, and the population is simulated 10 times. The left column (a, c, d) shows simulations without environmental stochasticity, while the right column (b,d,e) has the same level of environmental stochasticity shown in Fig. 16b. The top row (a,b) has no demographic stochasticity, while the second (c, d) and third (e,f) row shows the expected development with demographic stochasticity for populations starting with 1000 and 100 individuals, respectively.

3.3.2 Contamination data

The main studies on contaminants involving black-legged kittiwakes are listed in Appendix 1. Therefore, contamination data from Norwegian Spring-spawning herring, which forages in large parts of the Norwegian Sea, may give an indication of the level and trends of environmental contaminants (Tab. 3). The contamination levels are generally low compared to the levels seen in e.g. Baltic herring. The level of Cd may be increasing slightly, and individual fish may have Cd levels above the food security limits of EU (Miljøstatus 2013).

3.4 Discussion

A simple model of black-legged kittiwake population biology, using realistic parameters for mean and variation of survival rates, indicates that black-legged kittiwakes populations are sensitive to changes in adult survival as well as variability in chick survival. This is also expected to result in a high selection pressure for increased adult survival, confirming the conclusions of Lack (1968). The ability to relate model results to data was in our case severely limited by the lack of available data. However, for the two locations where we had a population time series, the steep decline indicated that either (1) adult survival in these locations is lower than found in the more northerly colonies where survival estimates exist, such as Hornøya and Anda, (2) sub-adult survival - the survival between chick and adult stage - may be higher than adult survival (not equal, as we assumed), or (3) chick mortality is extremely high. With the data we have at hand, it is not possible to make an assessment of which of these (not mutually exclusive) hypotheses.

Data on contamination is also scarce for southern bird colonies. Also, contaminants in black-legged kittiwakes have mainly been studied in Svalbard, where black-legged kittiwake populations are doing relatively good. Given the very close relationship between adult survival and population decline/growth in black-legged kittiwakes, even a moderate increase in mortality if adults could have quite a large effect on the population.

Finally, black-legged kittiwakes are extremely dependent on pelagic fish, which must be available in the surface water of the ocean for this non-diving species. A striking pattern is the poor performance of the southern colonies compared to more northern (and eastern) ones, which may lead us towards the hypothesis of a negative influence of the warming climate since 1980. Possibly supporting this is the information that the Runde population was growing during the 1960s and apparently reached a peak somewhere around 1970/80 (Barrett 1983). The North Atlantic also cooled during this period, reaching a minimum in 1974 (Fig. 20). There was in general an increase in black-legged kittiwake colonies both in mainland Norway and in Europe generally around 1970, and during the 1970s the species also spread to Spain and Portugal. This, climate may be one of the most important factors for this species.

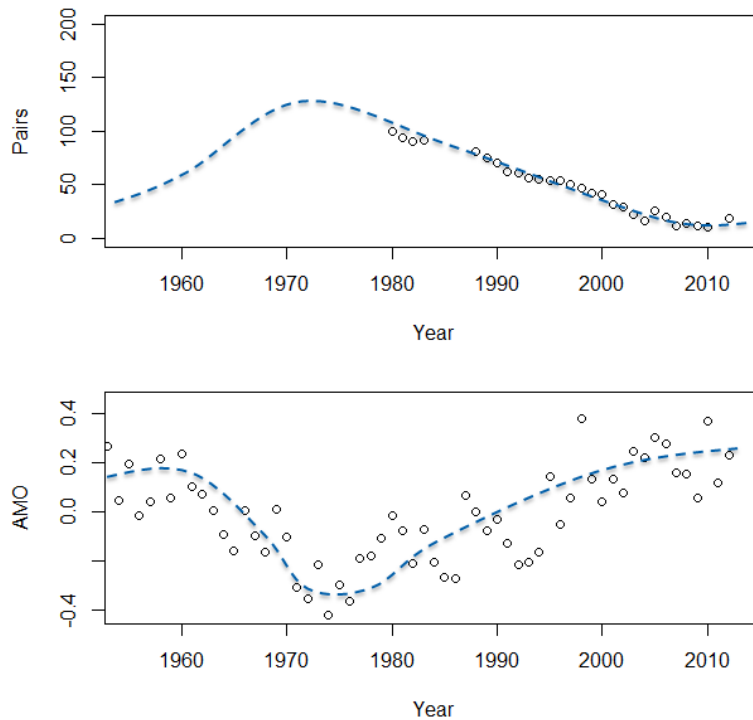


Figure 20. Black-legged kittiwake population trends at Runde (top; trends before 1980 are sketched according to information in the literature) compared to the time trend in Atlantic Multidecadal Oscillation (AMO; bottom).

3.5 Advice

For kittiwake, we will generally say the same as for cod: a diverse approach is more likely to return good and certain insight about what affects population dynamics. As typical of pelagic seabirds, the black-legged kittiwake is characterized by a life history of high adult survival and a small brood size. This is likely to be an adaptation to the a sparse, patchy and unpredictable food supply which varies substantially between years (Ricklefs 1990), resulting in a relatively frequent failure of successful breeding. This presents special challenges for studies and management of seabirds. For instance, failure of breeding in one or a few seasons is probably quite common also in a pristine environment. Also, whether a colony declines or is stable depends a lot on adult survival, which must be estimated by quite costly capture-mark-recapture studies. Also, as small changes in adult survival can have a large effect on the population, estimates must be quite precise in order to be meaningful, which requires a fairly large sample size and a research program running over many years. If a change in the environment leads to decreased (or increased) adult survival, it is likely to take several years to be detected with statistical significance. Finally, the adults spend much of the year in very remote areas, where both birds are hard to study, and the data on the environment (for instance fish abundance) are sparse. On the other hand, seabirds may be an indicator for the health of the environment in such remote areas. Thus, seabirds may certainly function as a "canary in the mine" for ongoing changes in the marine environment; however, saying for certain why the canary died may be difficult (Durant et al. 2009).

As black-legged kittiwakes are high on the marine food chain, one of the foremost uses of black-legged kittiwakes could be as "samplers" of the chemical environment in the ocean. Black-legged kittiwakes utilize an extremely wide range outside the breeding season, being distributed throughout the North Atlantic with a major concentration in central and western parts (Frederiksen et al. 2012). As ship-based surveys to these areas are very expensive, wide-ranging seabirds may be a cost-effective option for sampling. Contamination concentrations could be measured using blood/feathers of adult birds, which would enable recapture of the same birds, in order to follow development of individual development of contamination load and/or to analyse whether contamination load affects longevity. This could be combined with light-based archival geolocator tags to get information on each bird's movements. Such

tags, which record light level information which then is processed to give the bird's location (latitude and longitude), are much cheaper and lighter than satellite tags, and their precision is good enough considering the areas the black-legged kittiwakes use. This could also possibly reveal how much contaminants that is acquired during the chicken stage (from the parents' food provisioning), how much that is acquired later in life in "local" waters (the Norwegian Sea), and how much that is acquired in more remote ocean areas. Until now sampling of kittiwake eggs for contaminant analysis has largely been done once every 10 years, which is much too infrequent. As there is considerable variation between contaminant concentrations in individual birds, there is simply a need for more data to detect trends and patterns. While the contamination patterns may be the same for black-legged kittiwakes in Svalbard and on the mainland (due to their wide range and large overlap outside the breeding season; Frederiksen et al. 2012), this is not for certain, so there is also a need for sampling birds from a larger geographical range.

In conclusion, we have the following specific advice:

1. The current program (Seapop) should continue at least on the level it runs today
2. Sampling of eggs for measurements of contaminants has largely been done once every 10 years, which is much too infrequent
3. At least some sampling of contaminants should be done in more southerly colonies
3. Contaminants should also be collected from blood/feathers of adult birds to enable recapture of birds, possibly in combination with geolocator data

Table 3. The concentrations of contaminants in Norwegian Spring-spawning herring, the dominant herring stock along the Norwegian coast.

	Arsen (As) (mg/kg)	Bly (Pb) (mg/kg)	Dioksiner (PCDD/F) (ng TEQ/kg)	Dioksiner ¹ (ng TEQ/kg)	HCB	HCH	Kadmium (Cd) (mg/kg)	Polybromerte di-fenyl etere (Sum PBDE) (µg/kg)	Sum DDT (Pesticide) (µg/kg)	Sum PCB (PCB 7) (µg/kg)
1995	2 (1.1-2.8)	0.005 (<0.005-0.01)			1 (0.2-2.6)		<0.001		17	13
1999	2 (1-2.6)	0.005			2 (1-2.6)		0.005 (0.002-0.013)		10	
2001	2 (1-3.2)	0.02 (0.001-0.004)			0.6 (0.4-1)		0.005 (0.003-0.01)		5	8
2002	1 (0.7-2.5)	<0.04 (<0.04-0.09)			0.4 (0.25-0.69)	1 (0.35-1.73)	0.003 (<0.002-0.1)		6	6
2003	1.5 (1.3-1.7)	<0.008	0.87 (0.64-1.04)		2 (1.5-3.4)	<18	0.01 (0.004-0.013)	1.2 (1-1.6)	12	12
2004	2 (1.3-2.8)	0.003 (0.001-0.014)				<18	0.007 (0.004-0.011)	1.1 (0.6-1.6)	10 (6-16)	6.6 (3.8-9.8)
2005	1.8 (1.2-2.3)	<0.01								
2007	2.17 (0.8-4.3)	0.01 (<0.01- 0.1) *(a)	0.39 (0.14-2.3)	0.77 (0.24-3.5)			0.01 (<0.003- 0.052)	0.5 (0.09-3.1)		5 (1.4-24)
2011	1.5 (1.0-2.4)	(<0,01-0.01)	0.6 (0.3-1.1)	1.1 (0.7-2.2)			0.02 (0.01-0.05)	0.5 (0.3-1.1)		6.8 (4.3-12.6)

¹ Inkludert dioksinlignende PCB (PCDD/F + non-orto og mono-orto PCBs)

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Appendix A. Black-legged kittiwake contaminant studies (mainly Svalbard)

Bjørnøya/Barentshavet 1995, 1998

See Borgå et al. (2001, 2005, 2007)

Hornøya, early 1990s

See Espen Henriksen et al. (1996)

Egg samples every 10 years since 1983 (1983, 1993 og 2003)

See Helgason et al. (2008)

Ekspimentelle studier Kongsfjorden (fledglings)

See Helgason et al. (2010) and Hegseth et al. (2011)

IPY-prosjekt - Contaminants in Polar Regions 2007-2009

Kongsfjorden 2007 mai, july, oct

see Hallanger et al. 2001a, 2011b

Kongsfjorden 2008 and 2009 July

see Solheim (2010)

Lifdefjorden 2008 and 2009 (not published yet)

Framsenteret/ IPY prosjekt: the Birdhealth project

Blodprøver fra 2007, published. (Nordstad et al. 2012)

Blodprøver av krykkje årlig siden 2007 (before and after breeding) (not published yet?)

Centre d'Etudes Biologiques de Chize / CNRS / Institut Polaire Francais (Olivier Chastel)

Blodprøver av krykkje, Kongsfjorden mai/juni 2008 og 2011

see Nordstad et al. (2012) and Tartu et al. (2013)

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Appendix B. Datakilder

1) Torsk

- a) Data fra Havforskningsinstituttets strandnottokt (høst)
 - i) Metadata for stasjoner
 - (1) Navn på stasjon
 - (2) Posisjon (lengde- og breddegrad)
 - (3) Eksponering (subjektivt vurdert)
 - ii) Data på stasjonsnivå
 - (1) År
 - (2) Antall torsk alder 0 år
 - (3) Antall torsk alder 1 år + oppover
 - iii) Data på individnivå
 - (1) Kroppslengde
- b) Data på forurensing i tosk og blåskjell fra MILKYS-programmet (tidl. CEMP) (NB: viser kun de viktigste feltene)
For geografisk utbredelse, se fig. A1-A4 (de neste sidene)
 - i) Data på stasjonsnivå
 - (1) Navn på stasjon
 - (2) Posisjon (lengde- og breddegrad)
 - (3) Art (for blandprøver fra flere individer)
 - (4) Antall (for blandprøver fra flere individer)
 - ii) Data på individnivå
 - (1) Art
 - (2) Lengde
 - (3) Vekt
 - (4) Fettprosent, lever
 - iii) Data på prøvenivå
 - (1) Vev
 - (2) Parameter
 - (3) Verdi
 - (4) Enhet
- c) Data fra Statlig program for forurensingsovervåking
I hovedsak dioksiner og PCB
Struktur og felter – omtrent som over

2) Krykkje

- a) Tidsserier på antall par i koloniene Runde og Sklinna
<http://www.miljostatus.no/indikatorer-Norskehavet#Sjofugl>
 - b) Tall på voksen overlevelse, kullstørrelse og antall flyvedyktige unger fra enkeltår i overvåkede kolonier, hentet fra Seapops rapporter på www.seapop.no
-

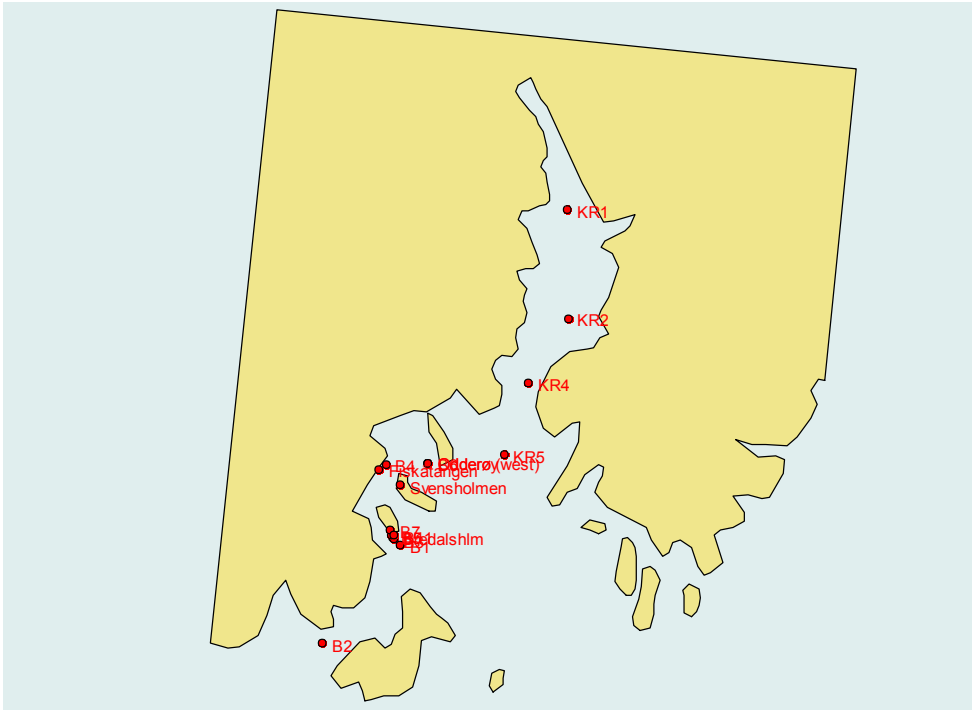


Fig. A3. Stasjoner med data for blåskjell, detaljkart for Kristianssandsfjorden / Tofdalsfjorden

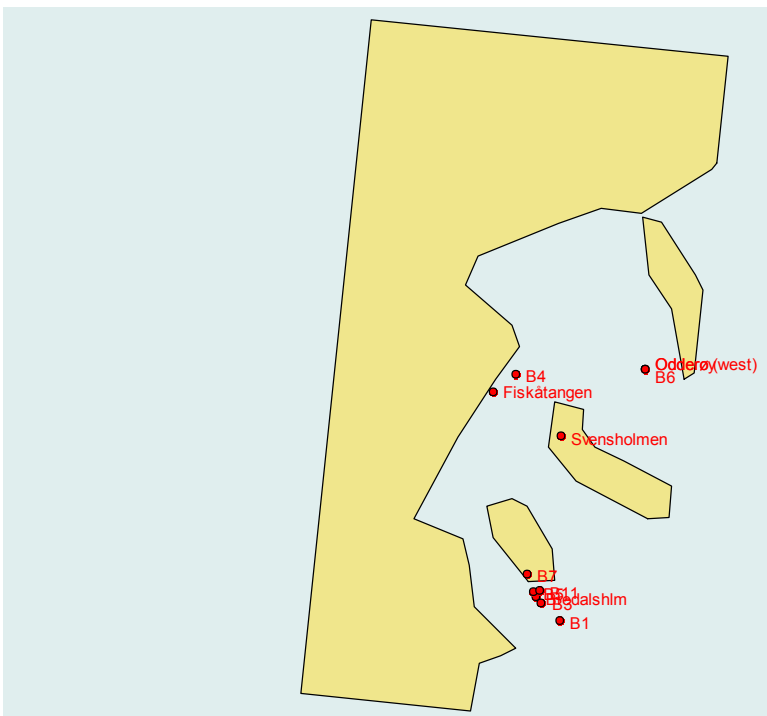


Fig. A4. Stasjoner med data for blåskjell, detaljkart for Kristianssandsfjorden (Odderøy / Vågsbygd / Bradgdøya)

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