**Contaminants description (Appendix S1)**

HCB was previously used as a fungicide and a wood preserving agent, but is also a by-product in many chemical processes, such as the production of chlorinated solvents and pesticides [1]. It is also released to the environment through incomplete combustion, e.g. in waste incineration and metallurgical industries. In Norway, HCB was released to the Grenlandfjord-system from the previous magnesium smelter activity in the area [2]. HCB is very persistent in the environment, but its physico-chemical properties renders it even more likely to undergo environmental re-cycling [1]. It can undergo atmospheric transportation over great distances through a repeated process of deposition, remobilization into the atmosphere, and re-deposition [1]. The International Agency for Research on Cancer (IARC) has classified HCB as a possible human carcinogen, based on animal evidence [3], and HCB can cause chronic toxicity, stress, and tissue damage to fish [4].

Cadmium (Cd) is a naturally occurring element on earth but human activities such as mining, smelting, and refining metal ores (especially zinc, lead, and copper) have increased its concentration in the natural environment [5]. Cd is also emitted into the atmosphere from fossil fuel burning, waste incineration, steel production, and material recycling (such as nickel-cadmium batteries or metal scraps) [5]. In Norway, Cd used to be found in high concentrations in fish and mussels tissue close to the zinc smelters in Sørfjorden and Odda. Cd is highly toxic to humans and bio-accumulates in the kidneys, liver, or bones, causing chronic toxic effects [5]. Cases of Cd poisoning include the “itai-itai” disease outbreak (“ouch-ouch” disease) in Japan in 1912, caused by the release of Cd into the agricultural run-off from a nearby mining plant. Cd can enter fish by passive diffusion across the gills or by the marine food chain and decreases their fitness by altering endocrine function, leading to reduced liver size, glycogen content, and body mass [6,7]. Cd can also disrupt the social interactions between fish [7,8].

Like Cd, mercury (Hg) is also a naturally occurring element on earth and also enters the environment through human activities such as mining, smelting, incineration, and manufacturing industries [5]. In Norway, Hg has been released by e.g., chloralkali industry in both the Grenlandfjord system and the Hvaler area [9]. In the aquatic environment, inorganic mercury can be transformed to methylmercury (especially by bacterial activity) which is more toxic and biomagnifies in the food chain [10]. Methylmercury is also a potent neurotoxin for human that can affect the memory, motor skill, and cardiovascular system. Cases of acute Hg poisoning include the “Minamata” disease in Japan in 1956 caused by the release of methylmercury to the Minamata bay by nearby industrial plants. Based on data on secondary poisoning of mammals and birds, the EU has set an Environmental Quality Standard (EQS) of 0.020 mg kg-1 in the tissue of biota (mainly fish). However, this level is exceeded by a large part of European monitoring sites. For instance, almost all freshwater fish sampled in Fennoscandia exceeds this limit [11].

**Pollution time-series reconstruction (Appendix S2)**

We fitted a spatio-temporal model to the pollution data (eq S1, Table S1). We assumed that pollution data was temporally correlated (1st order autocorrelation), but spatially uncorrelated between fjords (i.e. sites within fjord are correlated but not across fjords. Closest sites were about 1 kilometer apart). We tried to estimate the spatial correlation structure of the pollution data (both within fjords and across fjords) but the models failed to converge due to lack of data (some fjords had only one or two observations) and signal in the data. Extrapolation of the pollution level at each geographical unit within a fjord was then based on the average of the predicted site-level (pollution survey site, not beach seine) pollution within each fjord i.e. all geographical units within a fjord have the same pollution history. We therefore lost some local variability in pollution history but the sparsity of available data (on average 75% of the data were missing at the pollution survey site level and 60% at the fjord level between 1979-2015) seldom complicated the problem. However, we tried to account for uncertainties around the estimated pollution trajectories by generating 100 MCMC posterior sample of the pollution trajectories. The median pollution values (from the 100 MCMC) for each fjord and time was used as the reference case for testing the pollution effect in the model (and for model selection) but the 100 samples were then used to test the sensitivity of the best model to pollution uncertainty (Fig. S2-4).

**Reconstructing a time series of total mortality (Z) for cod age 2+ (Appendix S3)**

In order to reconstruct a possible total mortality time series for cod age 2+, we used two sources of data. One is the cod age data from a gillnet survey along Skagerrak and the other one is the ICES assessment reported estimate of average fishing mortality from age 2 to 4 (named “Fbar” in the ICES report) [12].

Cod age data comes from an annual autumn survey (November–December) conducted in five regions of Skagerrak using trammel gillnets. Each year (2001–2015 except 2009 where no survey was conducted), the same set of gillnets (45 mm mesh size) was set at the same sites in shallow near-shore waters (5–15 m depth). Cod was then sampled, measured, and otolith taken for age determination [13]. We used this data to then linearly regress the numbers at age *a+1*, at year *t+1*, *Na+1,y+1* against the numbers at age *a* and year *y*, *Na,y* for all sampled cod of age 2+ (while forcing the intercept at origin). Doing so, we obtained a crude estimate of Z for each year (based on the population dynamics assumption in eq S2, Table S1, for age 2+), assuming that the sampled population is closed with limited movement with the outer populations (the credibility of such hypothesis is contentious but this is the only source of data available to hope obtaining a guestimate of total mortality). Prior to performing the regression, data from all five regions were merged as there was not enough data to estimate an independent Z for each region.

In order to obtain a Z value for 2009 (no-survey-year), we performed the same above regression using the 2008 and 2010 data instead (i.e. a 2-year lag). The derived Z estimate was thus for 2 years therefore was halved to obtain the Z estimate for 2008 and 2009 (assuming the same Z for both years).

As gillnet survey was not conducted before 2001, we used the estimates of average F from the ICES assessment (for ages 2-4) to extrapolate the Z values from 1978-2000. More specifically, we scaled up the ICES estimate of “Fbar” (by roughly 0.2 which would be similar to the natural mortality estimate of cod) so that the 2001 estimate of F from the ICES report and the Z value from the gillnet data matched. Doing so, resulted in the Z time series (1978-2015) shown in Fig. S14.

## Study limitations (Appendix S4)

Using the best available science and data, we built in this study a spatially explicit population dynamics model to evaluate the impact of pollution history of natural fish population. There exists, however, other knowledges that we could not account for in the model. Other studies have shown for example that temperature can influence the growth, reproductive output, and the timing of maturation in fishes [14–16]. While interesting, this would require extensive data on temperature at the scale of analysis and potentially auxiliary data on coastal cod growth, recruitment, or maturation which are currently unavailable. Similarly, habitat features (e.g. presence of eelgrass) are important characteristics that can affect juvenile fish survival and growth [17,18]. However, site-level model (which has some habitat information) could not be run in this study due to lack of data. A metric representing the average eelgrass condition could have been created at the scale of the geographical unit but such effect would have been confounded with the geographical unit level effect (i.e. the average local productivity parameter ) that we already included in the model. Furthermore, [16] suggested that inter-cohort density dependence plays a large role in cod recruitment. We also tested for its effect in our models (results not shown here) but it did not improve the model fit to the data (based on the model selection criteria used in this study). We therefore decided to leave it out from the final model. This contrasting result could be explained by the finer spatial structure of our model and the use of length composition data (instead of age composition data). By scaling down the analysis from fjords to geographical units, the variance that was explained before by the density dependent parameter was now better explained by differences in growth or recruitment deviation at the geographical unit level. Additionally, by using the length composition data directly, we propagated the model uncertainty throughout the model, potentially affecting some parameter estimation. Also, some differences could be attributed to the difference in the computation approach i.e Bayesian vs. frequentist. Last but not the least, the three chosen contaminants must be regarded as proxies of the complex contamination status, as there are numerous contaminants or other xenobiotics that are likely to covary with one or more of our three selected contaminants. The causal relationships discussed in this study must be seen as possible explanations.

**Table S1**. Table of equations used in the study

|  |  |  |
| --- | --- | --- |
| **Modelled processes** | **Equations** | **Parameter description** |
| Spatio-temporal model for the pollution data  (eq S1) |  | *Xi,y*: measured contaminant concentration at location *i* and year *y*  predicted value at location *i* andyear *y*  average pollution level in the fjord that location *i* belongs to  average pollution for year *y*  *ρ:* temporal autocorrelation parameter  location specific process-error  : variance for the interannual variability in pollution trend  : fjord specific process error variance |
| Cod population dynamics (eq S2) |  | : numbers at age *a*, location *i* and year *y*  : spawning stock biomass at location *i* and year *y*  : recruitment deviation for location *i* centered around with variance  : recruitment deviation for year *y* centered around 0 with variance  : recruitment deviation for location *i* and year *y* centered around 0 with variance  : survival at location *i* and year *y* centered around 0 with variance  *Z*: total mortality rate  *Wa*: weight at age *a*  *Ma*: maturity at age *a* |
| Cod growth (eq S3) |  | : length at age *a* at location *i*  *Ki*: growth coefficient for location *i*  : asymptotic length  : length variability at age *a* |
| Age-length transition probability matrix (eq S4) |  | : probability of belonging to length bin *l* (5cm bin size) at age *a* and location *i*  : the standard normal cumulative distribution  : lower bound for the length bin *l* |
| Survey selectivity (eq S5) |  | length at 50% selectivity  difference in length between 5% and 50% selectivity. |
| From numbers at age to numbers at length (eq S6) |  | : total number of animals within the length bin *l* (a 5cm length bin was used), age class *a*,location *i*,andsurvey year *y* |
| Catch of cod (eq S7) |  | : the average predicted catch at site *i* and year *y*  : catchability at location *i*  : catch overdispersion parameter |
| Functional form of the pollution effect (eq S8) |  | *α*: slope of the linear effect of pollution  *β*:exponential effect of pollution  *pmax*: maximum pollution level that leads to a complete elimination of recruitment  *pmod*: pollution level at which maximum change in recruitment reduction happens (the inflection point). |

**Table S2**. List of abbreviation used to characterize model name.

|  |  |
| --- | --- |
| **Abbreviation** | **Description** |
| No\_pollution | No pollution effect |
| HG | Mercury as pollutant |
| CD | Cadmium as pollutant |
| HCB | HCB as pollutant |
| lin | Linear effect of pollutant |
| exp | Exponential effect of pollutant |
| sig | Sigmoidal effect of pollutant |
| 0 | Current year pollution affects current year recruits’ survival |
| 1 | Last year pollution affects current year recruits’ survival |
| 2 | Pollution two years ago affects current year recruits’ survival |
| single | The pollution effect is the same across all fjords |
| fjord | The pollution effect can differ between fjords |

**Table S3**: Model selection results. ✓ indicates no problem and X indicates the presence of a problem. The row shaded in grey highlights the model with the lowest **Δ**AIC for each combination of pollutant and functional form of the pollution effect (i.e. selectes the best time lag). See Table S4 for further model selection results.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Model name\*** | **ΔAIC** | **Convergence** | **Identifiability** | **Fit to data** |
| No\_pollution | 36.8 | ✓ | ✓ | ✓ |
| CD\_exp\_0\_single | 36.9 | ✓ | ✓ | ✓ |
| CD\_exp\_0\_fjord | 12.7 | ✓ | ✓ | ✓ |
| CD\_exp\_1\_single | 24.4 | X | X | ✓ |
| CD\_exp\_1\_fjord | 12.5 | ✓ | X | ✓ |
| CD\_exp\_2\_single | 35.1 | ✓ | ✓ | ✓ |
| CD\_exp\_2\_fjord | 8.1 | ✓ | ✓ | ✓ |
| CD\_sig\_0\_single | 40.8 | X | X | ✓ |
| CD\_sig\_0\_fjord | 68.8 | X | X | ✓ |
| CD\_sig\_1\_single | 32.0 | X | X | ✓ |
| CD\_sig\_1\_fjord | 56.0 | X | X | ✓ |
| CD\_sig\_2\_single | 28.3 | ✓ | X | ✓ |
| CD\_sig\_2\_fjord | 45.6 | X | X | ✓ |
| CD\_lin\_0\_single | 37.7 | ✓ | ✓ | ✓ |
| CD\_lin\_0\_fjord | 28.9 | ✓ | ✓ | ✓ |
| CD\_lin\_1\_single | 35.6 | ✓ | ✓ | ✓ |
| CD\_lin\_1\_fjord | 25.2 | X | X | X |
| CD\_lin\_2\_single | 30.9 | X | X | X |
| CD\_lin\_2\_fjord | 28.9 | ✓ | ✓ | ✓ |
| HG\_exp\_0\_single | 38.8 | ✓ | X | ✓ |
| HG\_exp\_0\_fjord | 30.5 | X | X | ✓ |
| HG\_exp\_1\_single | 37.8 | ✓ | X | ✓ |
| HG\_exp\_1\_fjord | 13.8 | X | X | ✓ |
| HG\_exp\_2\_single | 37.7 | ✓ | X | ✓ |
| HG\_exp\_2\_fjord | 5.4 | X | X | ✓ |
| HG\_sig\_0\_single | 40.8 | ✓ | X | ✓ |
| HG\_sig\_0\_fjord | 51.4 | X | X | ✓ |
| HG\_sig\_1\_single | 38.7 | ✓ | ✓ | ✓ |
| HG\_sig\_1\_fjord | 14.6 | X | X | ✓ |
| HG\_sig\_2\_single | 39.7 | ✓ | ✓ | ✓ |
| HG\_sig\_2\_fjord | 9.7 | X | X | ✓ |
| HG\_lin\_0\_single | 38.8 | ✓ | X | ✓ |
| HG\_lin\_0\_fjord | 33.0 | X | X | ✓ |
| HG\_lin\_1\_single | 37.5 | ✓ | X | ✓ |
| HG\_lin\_1\_fjord | 17.7 | ✓ | X | ✓ |
| HG\_lin\_2\_single | 37.7 | ✓ | X | ✓ |
| HG\_lin\_2\_fjord | 33.0 | X | X | ✓ |
| HCB\_exp\_0\_single | 212.4 | X | X | ✓ |
| HCB\_exp\_0\_fjord | 30.4 | X | X | ✓ |
| HCB\_exp\_1\_single | 38.8 | ✓ | ✓ | ✓ |
| HCB\_exp\_1\_fjord | 22.6 | X | X | X |
| HCB\_exp\_2\_single | 38.2 | ✓ | ✓ | ✓ |
| HCB\_exp\_2\_fjord | 47.3 | ✓ | ✓ | ✓ |
| HCB\_sig\_0\_single | 40.8 | X | X | ✓ |
| HCB\_sig\_0\_fjord | 57.1 | X | X | ✓ |
| HCB\_sig\_1\_single | 40.8 | X | X | ✓ |
| HCB\_sig\_1\_fjord | 41.3 | X | X | ✓ |
| HCB\_sig\_2\_single | 40.8 | X | X | ✓ |
| HCB\_sig\_2\_fjord | 1907.5 | X | X | ✓ |
| HCB\_lin\_0\_single | 38.8 | ✓ | ✓ | ✓ |
| HCB\_lin\_0\_fjord | 42.9 | ✓ | X | ✓ |
| HCB\_lin\_1\_single | 38.8 | ✓ | ✓ | ✓ |
| HCB\_lin\_1\_fjord | 32.4 | X | X | X |
| HCB\_lin\_2\_single | 38.4 | ✓ | ✓ | ✓ |
| HCB\_lin\_2\_fjord | 42.9 | ✓ | X | ✓ |
| CD+HG\_exp\_0\_single | 38.8 | ✓ | ✓ | ✓ |
| CD+HG\_exp\_0\_fjord | 19.9 | ✓ | ✓ | ✓ |
| CD+HG\_exp\_1\_single | 26.5 | X | X | ✓ |
| CD+HG\_exp\_1\_fjord | 10.1 | ✓ | X | ✓ |
| CD+HG\_exp\_2\_single | 36.4 | ✓ | ✓ | ✓ |
| CD+HG\_exp\_2\_fjord | 2.9 | ✓ | ✓ | ✓ |
| CD+HG\_sig\_0\_single | 40.8 | X | X | ✓ |
| CD+HG\_sig\_0\_fjord | 75.3 | X | X | ✓ |
| CD+HG\_sig\_1\_single | 32.9 | X | X | X |
| CD+HG\_sig\_1\_fjord | 41.1 | X | X | ✓ |
| CD+HG\_sig\_2\_single | 29.1 | ✓ | X | ✓ |
| CD+HG\_sig\_2\_fjord | 39.1 | X | X | ✓ |
| CD+HG\_lin\_0\_single | 38.8 | ✓ | ✓ | ✓ |
| CD+HG\_lin\_0\_fjord | 30.8 | ✓ | ✓ | ✓ |
| CD+HG\_lin\_1\_single | 31.9 | X | X | ✓ |
| CD+HG\_lin\_1\_fjord | 19.3 | ✓ | ✓ | ✓ |
| CD+HG\_lin\_2\_single | 38.8 | X | X | ✓ |
| CD+HG\_lin\_2\_fjord | 108.7 | X | X | X |
| CD+HCB\_exp\_0\_single | 38.8 | ✓ | ✓ | ✓ |
| CD+HCB\_exp\_0\_fjord | 16.1 | ✓ | ✓ | ✓ |
| CD+HCB\_exp\_1\_single | 18.9 | X | X | ✓ |
| CD+HCB\_exp\_1\_fjord | 32.2 | X | X | ✓ |
| CD+HCB\_exp\_2\_single | 36.0 | ✓ | ✓ | ✓ |
| CD+HCB\_exp\_2\_fjord | 16.2 | X | X | ✓ |
| CD+HCB\_sig\_0\_single | 40.8 | X | X | ✓ |
| CD+HCB\_sig\_0\_fjord | 57.1 | X | X | ✓ |
| CD+HCB\_sig\_1\_single | 40.8 | X | X | ✓ |
| CD+HCB\_sig\_1\_fjord | 50.5 | X | X | ✓ |
| CD+HCB\_sig\_2\_single | 37.6 | ✓ | X | ✓ |
| CD+HCB\_sig\_2\_fjord | 11.2 | X | X | ✓ |
| CD+HCB\_lin\_0\_single | 38.8 | ✓ | ✓ | ✓ |
| CD+HCB\_lin\_0\_fjord | 52.8 | X | X | ✓ |
| CD+HCB\_lin\_1\_single | 20.4 | X | X | ✓ |
| CD+HCB\_lin\_1\_fjord | 30.8 | X | X | ✓ |
| CD+HCB\_lin\_2\_single | 37.0 | ✓ | ✓ | ✓ |
| CD+HCB\_lin\_2\_fjord | 37.0 | ✓ | ✓ | ✓ |
| HG+HCB\_exp\_0\_single | 38.8 | ✓ | ✓ | ✓ |
| HG+HCB\_exp\_0\_fjord | 27.4 | X | X | ✓ |
| HG+HCB\_exp\_1\_single | 38.2 | ✓ | ✓ | ✓ |
| HG+HCB\_exp\_1\_fjord | 17.2 | ✓ | ✓ | ✓ |
| HG+HCB\_exp\_2\_single | 37.3 | ✓ | ✓ | ✓ |
| HG+HCB\_exp\_2\_fjord | 6.5 | X | X | ✓ |
| HG+HCB\_sig\_0\_single | 40.8 | X | X | ✓ |
| HG+HCB\_sig\_0\_fjord | 68.2 | X | X | ✓ |
| HG+HCB\_sig\_1\_single | 40.8 | X | X | ✓ |
| HG+HCB\_sig\_1\_fjord | 64.9 | X | X | ✓ |
| HG+HCB\_sig\_2\_single | 37.6 | ✓ | X | ✓ |
| HG+HCB\_sig\_2\_fjord | 22.2 | X | X | ✓ |
| HG+HCB\_lin\_0\_single | 38.8 | ✓ | X | ✓ |
| HG+HCB\_lin\_0\_fjord | 52.8 | X | X | ✓ |
| HG+HCB\_lin\_1\_single | 38.2 | ✓ | ✓ | ✓ |
| HG+HCB\_lin\_1\_fjord | 33.6 | ✓ | ✓ | ✓ |
| HG+HCB\_lin\_2\_single | 37.7 | ✓ | ✓ | ✓ |
| HG+HCB\_lin\_2\_fjord | 36.9 | X | X | ✓ |
| CD+HG+HCB\_exp\_0\_single | 38.8 | ✓ | X | ✓ |
| CD+HG+HCB\_exp\_0\_fjord | 20.0 | ✓ | ✓ | ✓ |
| CD+HG+HCB\_exp\_1\_single | 35.2 | X | X | ✓ |
| CD+HG+HCB\_exp\_1\_fjord | 12.2 | ✓ | X | ✓ |
| CD+HG+HCB\_exp\_2\_single | 36.2 | ✓ | ✓ | ✓ |
| CD+HG+HCB\_exp\_2\_fjord | 12.4 | ✓ | X | ✓ |
| CD+HG+HCB\_sig\_0\_single | 29.1 | ✓ | X | ✓ |
| CD+HG+HCB\_sig\_0\_fjord | 57.1 | X | X | ✓ |
| CD+HG+HCB\_sig\_1\_single | 33.9 | X | X | X |
| CD+HG+HCB\_sig\_1\_fjord | 48.3 | X | X | ✓ |
| CD+HG+HCB\_sig\_2\_single | 40.8 | X | X | ✓ |
| CD+HG+HCB\_sig\_2\_fjord | 65.6 | X | X | ✓ |
| CD+HG+HCB\_lin\_0\_single | 38.8 | ✓ | X | ✓ |
| CD+HG+HCB\_lin\_0\_fjord | 38.8 | ✓ | X | ✓ |
| CD+HG+HCB\_lin\_1\_single | 33.0 | X | X | X |
| CD+HG+HCB\_lin\_1\_fjord | 22.9 | ✓ | ✓ | ✓ |
| CD+HG+HCB\_lin\_2\_single | 36.6 | ✓ | ✓ | ✓ |
| CD+HG+HCB\_lin\_2\_fjord | 28.8 | ✓ | ✓ | ✓ |

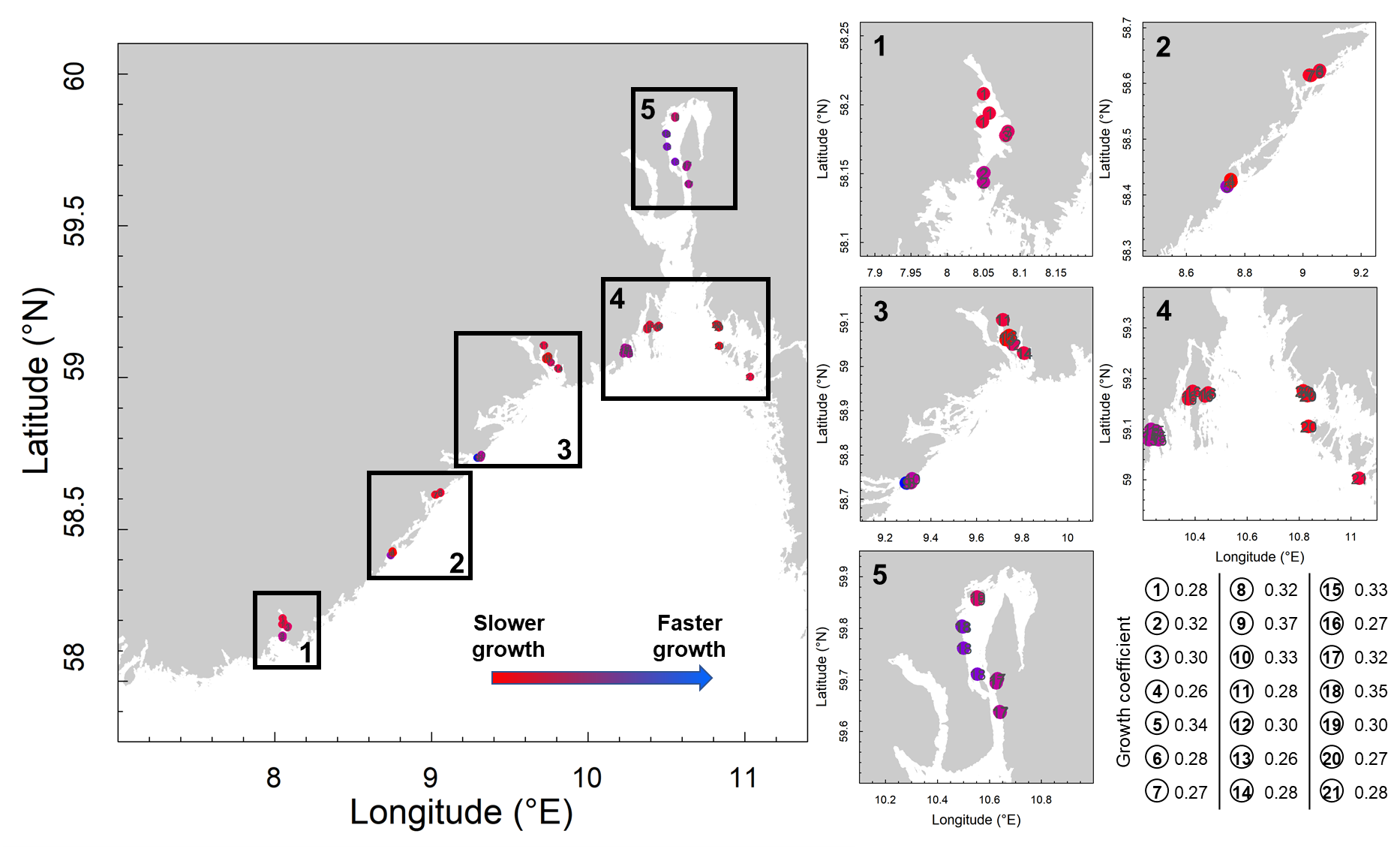
\* see the meaning of the abbreviations used for model names in Table S2.

**Table S4**: Further model selection results (performed on the grey shaded rows in Table S3) to eliminate non-significant fjord effects (if any). ✓ indicates no problem and X indicates the presence of a problem. The row shed in grew indicates the most parsimonious model (i.e. model without any problems and with the lowest **Δ**AIC).

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Model name\*** | **ΔAIC** | **Convergence** | **Identifiability** | **Fit to data** | **Local fjord effect** |
| No\_pollution | 36.8 | ✓ | ✓ | ✓ | |  |  |  |  |  |  |  |  | | --- | --- | --- | --- | --- | --- | --- | --- | | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | |
| CD\_exp\_2\_fjord | 8.1 | ✓ | ✓ | ✓ | |  |  |  |  |  |  |  |  | | --- | --- | --- | --- | --- | --- | --- | --- | | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | |
| CD\_lin\_1\_fjord | 27.5 | ✓ | ✓ | ✓ | |  |  |  |  |  |  |  |  | | --- | --- | --- | --- | --- | --- | --- | --- | | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | |
| HG\_exp\_2\_fjord | 5.4 | X | X | ✓ | |  |  |  |  |  |  |  |  | | --- | --- | --- | --- | --- | --- | --- | --- | | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | |
| HG\_exp\_2\_fjord | 1.4 | ✓ | X | ✓ | |  |  |  |  |  |  |  |  | | --- | --- | --- | --- | --- | --- | --- | --- | | 1 | 2 |  |  | 5 | 6 | 7 | 8 | |
| HG\_sig\_2\_fjord | 9.7 | X | X | ✓ | |  |  |  |  |  |  |  |  | | --- | --- | --- | --- | --- | --- | --- | --- | | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | |
| **HG\_sig\_2\_fjord** | **0.0** | **✓** | **✓** | **✓** | |  |  |  |  |  |  |  |  | | --- | --- | --- | --- | --- | --- | --- | --- | |  |  |  |  | **5** | **6** | **7** |  | |
| HG\_lin\_1\_fjord | 17.7 | ✓ | X | ✓ | |  |  |  |  |  |  |  |  | | --- | --- | --- | --- | --- | --- | --- | --- | | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | |
| HG\_lin\_1\_fjord | 13.7 | ✓ | X | ✓ | |  |  |  |  |  |  |  |  | | --- | --- | --- | --- | --- | --- | --- | --- | | 1 | 2 |  |  | 5 | 6 | 7 | 8 | |
| HCB\_exp\_1\_fjord | 22.6 | X | X | X | |  |  |  |  |  |  |  |  | | --- | --- | --- | --- | --- | --- | --- | --- | | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | |
| HCB\_exp\_1\_fjord | -1.2 | X | X | X | |  |  |  |  |  |  |  |  | | --- | --- | --- | --- | --- | --- | --- | --- | |  | 2 | 3 |  | 5 | 6 |  | 8 | |
| HCB\_lin\_1\_fjord | 32.4 | X | X | X | |  |  |  |  |  |  |  |  | | --- | --- | --- | --- | --- | --- | --- | --- | | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | |
| HCB\_lin\_1\_fjord | 20.8 | X | X | X | |  |  |  |  |  |  |  |  | | --- | --- | --- | --- | --- | --- | --- | --- | |  | 2 | 3 |  | 5 | 6 |  | 8 | |
| CD+HG\_exp\_2\_fjord | 2.9 | ✓ | ✓ | ✓ | |  |  |  |  |  |  |  |  | | --- | --- | --- | --- | --- | --- | --- | --- | | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | |
| CD+HG\_lin\_1\_fjord | 19.3 | ✓ | ✓ | ✓ | |  |  |  |  |  |  |  |  | | --- | --- | --- | --- | --- | --- | --- | --- | | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | |
| CD+HG\_lin\_1\_fjord | 8.0 | X | X | ✓ | |  |  |  |  |  |  |  |  | | --- | --- | --- | --- | --- | --- | --- | --- | |  |  |  |  | 5 |  |  |  | |
| CD+HCB\_exp\_0\_fjord | 16.1 | ✓ | ✓ | ✓ | |  |  |  |  |  |  |  |  | | --- | --- | --- | --- | --- | --- | --- | --- | | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | |
| CD+HCB\_exp\_0\_fjord | 9.5 | ✓ | ✓ | ✓ | |  |  |  |  |  |  |  |  | | --- | --- | --- | --- | --- | --- | --- | --- | |  |  |  |  | 5 | 6 | 7 |  | |
| CD+HCB\_sig\_2\_fjord | 11.2 | X | X | ✓ | |  |  |  |  |  |  |  |  | | --- | --- | --- | --- | --- | --- | --- | --- | | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | |
| CD+HCB\_sig\_2\_fjord | 7.2 | X | X | ✓ | |  |  |  |  |  |  |  |  | | --- | --- | --- | --- | --- | --- | --- | --- | | 1 | 2 | 3 | 4 | 5 |  | 7 | 8 | |
| HG+HCB\_exp\_2\_fjord | 6.5 | X | X | ✓ | |  |  |  |  |  |  |  |  | | --- | --- | --- | --- | --- | --- | --- | --- | | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | |
| HG+HCB\_sig\_2\_fjord | 22.2 | X | X | ✓ | |  |  |  |  |  |  |  |  | | --- | --- | --- | --- | --- | --- | --- | --- | | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | |
| HG+HCB\_sig\_2\_fjord | 1.0 | ✓ | ✓ | ✓ | |  |  |  |  |  |  |  |  | | --- | --- | --- | --- | --- | --- | --- | --- | |  |  |  |  | 5 |  |  |  | |
| HG+HCB\_lin\_1\_fjord | 33.6 | ✓ | ✓ | ✓ | |  |  |  |  |  |  |  |  | | --- | --- | --- | --- | --- | --- | --- | --- | | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | |
| HG+HCB\_lin\_1\_fjord | 23.7 | ✓ | ✓ | ✓ | |  |  |  |  |  |  |  |  | | --- | --- | --- | --- | --- | --- | --- | --- | |  |  |  |  | 5 | 6 | 7 |  | |
| CD+HG+HCB\_exp\_1\_fjord | 12.2 | ✓ | X | ✓ | |  |  |  |  |  |  |  |  | | --- | --- | --- | --- | --- | --- | --- | --- | | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | |
| CD+HG+HCB\_lin\_1\_fjord | 22.9 | ✓ | ✓ | ✓ | |  |  |  |  |  |  |  |  | | --- | --- | --- | --- | --- | --- | --- | --- | | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | |
| CD+HG+HCB\_lin\_1\_fjord | 18.7 | X | X | ✓ | |  |  |  |  |  |  |  |  | | --- | --- | --- | --- | --- | --- | --- | --- | |  |  |  |  | 5 |  |  |  | |

**Table S5**. Parameter estimates – mean and standard deviation (s.d.) – from the most parsimonious model

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Parameter** | | **Estimated**  **(Y/N)** | **Best model** | |
| **Symbol** | **Definition** |  | **Mean** | **s.d.** |
|  | Log variability in catch | Y | 0.17 | 0.03 |
|  | Log average recruitment variability by year | Y | 0.21 | 0.14 |
|  | Log spatio-temporal recruitment variability | Y | -0.08 | 0.06 |
|  | Log average recruitment variability by location | Y | -10.60 | 2.75e3 |
|  | Log variability in survival rate from recruits to age1 | Y | -0.93 | 0.09 |
|  | Average recruitment productivity | Y | 1.80 | 0.23 |
|  | Average survival rate from recruits to age1 | Y | 1.19 | 0.03 |
|  | Number of recruits in 1980 | Y | |  |  |  |  |  |  |  | | --- | --- | --- | --- | --- | --- | --- | | 7.93 | 6.72 | 7.80 | 6.98 | 6.58 | -12.5 | 6.38 | | 5.26 | 5.17 | 5.60 | 6.70 |  |  |  | | |  |  |  |  |  |  |  | | --- | --- | --- | --- | --- | --- | --- | | 0.47 | 0.71 | 0.96 | 0.61 | 0.79 | 7.7e3 | 0.67 | | 1.02 | 0.37 | 0.41 | 0.38 |  |  |  | |
|  | Number of age1 cod in 1980 | Y | |  |  |  |  |  |  |  | | --- | --- | --- | --- | --- | --- | --- | | 5.51 | 2.52 | 4.79 | 3.49 | 2.87 | 7.84 | 6.06 | | 6.47 | 5.60 | 3.86 | 5.54 |  |  |  | | |  |  |  |  |  |  |  | | --- | --- | --- | --- | --- | --- | --- | | 0.49 | 0.95 | 0.79 | 0.70 | 0.95 | 0.52 | 0.53 | | 0.69 | 0.33 | 0.54 | 0.37 |  |  |  | |
|  | Growth coefficient | Y | |  |  |  |  |  |  |  | | --- | --- | --- | --- | --- | --- | --- | | -1.28 | -1.14 | -1.21 | -1.34 | -1.07 | -1.29 | -1.31 | | -1.14 | -0.99 | -1.12 | -1.27 | -1.21 | -1.35 | -1.26 | | -1.12 | -1.30 | -1.13 | -1.05 | -1.19 | -1.32 | -1.27 | | |  |  |  |  |  |  |  | | --- | --- | --- | --- | --- | --- | --- | | 0.02 | 0.02 | 0.02 | 0.03 | 0.03 | 0.08 | 0.05 | | 0.03 | 0.02 | 0.04 | 0.03 | 0.03 | 0.03 | 0.04 | | 0.02 | 0.01 | 0.02 | 0.02 | 0.04 | 0.01 | 0.09 | |
|  | Asymptotic length | N | 70 | NA |
|  | Variance around the length at age *a* | N | 5 | NA |
|  | “Age” at length 0 | N | -0.5 | NA |
| *Z* | Total mortality rate | N | 0.916 | NA |
| *L50* | Length at 50% selectivity | N | 30 | NA |
| *ldiff* | Length between 50% and 95% selectivity | N | 10 | NA |
|  | Weight at age | N | |  |  |  |  |  |  |  | | --- | --- | --- | --- | --- | --- | --- | | 0.00 | 0.10 | 0.62 | 1.2 | 1.78 | 2.37 | 3.00 | | NA |
|  | Maturity at age | N | |  |  |  |  |  |  |  | | --- | --- | --- | --- | --- | --- | --- | | 0.00 | 0.04 | 0.18 | 0.53 | 0.86 | 0.97 | 1.00 | | NA |



**Fig. S1**: Variability in juvenile cod growth at beach seine sites (filled circles) along the Skagerrak coast. Sites have been combined into geographical units by spatial proximity (21 in total. The unit number is indicated for each site). All analyses have been performed at the unit level (the smallest spatial scale possible for analysis) due to data limitation. Boxes on the right are zoom-in plots from different regions along the coast. Color gradient from red (slower) to blue (faster) indicate the relative difference in growth speed.



**Fig. S2**: 100 MCMC runs (solid grey lines) of the reconstructed mercury pollution time series (predicted values without observation error) with the reference mercury time series (solid black time) used in the model. Observed values are represented with open dots.



**Fig. S3**: The mean reconstructed cadmium time series i.e. the reference time series (solid black time) and the 95% predictive interval (grey color) based on 100 MCMC runs.



**Fig. S4**: The mean reconstructed HCB time series i.e. the reference time series (solid black time) and the 95% predictive interval (grey color) based on 100 MCMC runs.



**Fig. S5**: Model sensitivity to the assumed Z values.

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**Fig. S6**: Model sensitivity to the assumed values.

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**Fig. S7**: Model sensitivity to the assumed size at 50% selectivity (L50).



**Fig. S8**: Model sensitivity to the assumed slope of the selectivity curve (Ldiff).



**Fig. S9**: Difference in the spawning stock biomass trajectories between the most parsimonious model with the pollution effect (purple line) and the null model without the pollution effect (black line).



**Fig. S10**: Estimate of pollution effect from the best model fitted to different reconstructed pollution time series.



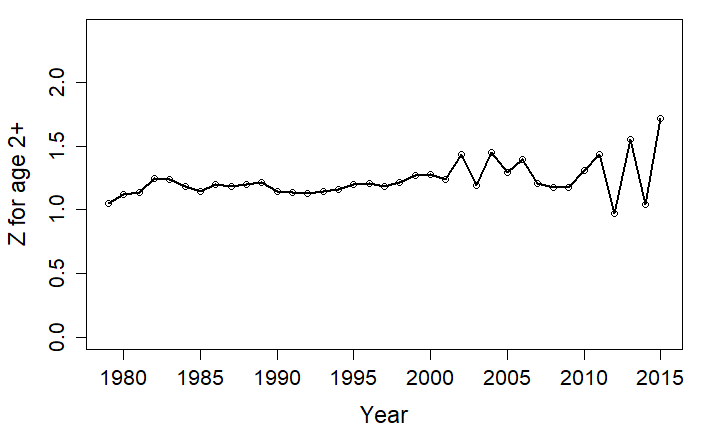
**Fig. S11**: Mean estimates of spawning stock biomass for each of the 100MCMC reconstructed Hg time series. The lines in grey are for each MCMC iteration and the black line is the Base case run. No standard deviation around SSB estimates are shown.



**Fig. S12**: Variability in growth parameter estimate based on the simulation-estimation. The boxplot shows the range of estimated growth values from the simulation exercise and the cross indicates the true value used for simulating the data.



**Fig. S13**: The average estimated recruitment trajectory (a-u) and their 95% confidence interval by geographic units within different fjords. Thick black lines are the average and the shaded area represent the 95% confidence interval. All recruitment estimates from this model appeared to be reliable based on the simulation study (i.e. the recruitment estimates (with their 95% confidence interval) from simulated data (n=100) all included the true value more than 50% of the time).



**Fig. S14**: Time series of reconstructed Z values using data from the gillnet survey along Skagerrak (for 2001-2015) and the average estimated F values for age (2-4) from the ICES report (for 1978-2000). The ICES’s data was rescaled to the gillnet data using the 2001 value.

# Reference list

1. Barber JL, Sweetman AJ, Van Wijk D, Jones KC. 2005 Hexachlorobenzene in the global environment: Emissions, levels, distribution, trends and processes. *Sci. Total Environ.* **349**, 1–44. (doi:10.1016/j.scitotenv.2005.03.014)

2. Knutzen J, Bjerkeng B, Næs K, Schlabach M. 2003 Polychlorinated dibenzofurans/dibenzo-p-dioxins (PCDF/PCDDS) and other dioxin-like substances in marine organisms from the Grenland fjords, S. Norway, 1975-2001: Present contamination levels, trends and species specific accumulation of PCDF/PCDD congeners. *Chemosphere* **52**, 745–760. (doi:10.1016/S0045-6535(03)00102-4)

3. IARC. 2001 IARC monographs on the evaluation of carcinogenic risks to humans. **79**.

4. Laska AL, Bartell CK, Condie DB, W BJ, Evans RL, Laseter JL. 1978 Acute and chronic effects of hexachlorobenzene and hexechlorobutadiene in Red Swamp crayfish (Procambarus clarki) and selected fish species. *Toxicol. Appl. Pharmacol.* **43**, 1–12.

5. Bosch AC, O’Neill B, Sigge GO, Kerwath SE, Hoffman LC. 2016 Heavy metals in marine fish meat and consumer health: A review. *J. Sci. Food Agric.* **96**, 32–48. (doi:10.1002/jsfa.7360)

6. Ricard AC, Daniel C, Anderson P, Hontela A. 1998 Effects of subchronic exposure to cadmium chloride on endocrine and metabolic functions in rainbow trout Oncorhynchus mykiss. *Arch. Environ. Contam. Toxicol.* **34**, 377–381.

7. Newman MC, Clements WH. 2008 *Ecotoxicology: a comprehensive treatment*. Boca Raton, FL: CRC Press.

8. Sloman KA, Scott GR, Diao Z, Rouleau C, Wood CM, McDonald DG. 2003 Cadmium affects the social behaviour of rainbow trout, Oncorhynchus mykiss. *Aquat. Toxicol.* **65**, 171–185. (doi:10.1016/S0166-445X(03)00122-X)

9. Climate and pollution agency. 2010 Norway’s action plan for reducing mercury releases - 2010.

10. Wolfe MF, Schwarzbach S, Sulaiman RA. 1998 Effects of mercury on wildlife: a comprensive review. *Environ. Toxicol. Chem.* **17**, 146–160.

11. Braaten HF V *et al.* 2017 Spatial and temporal trends of mercury in freshwater fish in Fennoscandia (1965-2015). (doi:10.13140/RG.2.2.16756.04485)

12. ICES. 2017 Report of the Working Group on Assessment of Demersal Stocks in the North Sea and Skagerrak (2017), 26 April–5 May 2017, ICES HQ. ICES CM 2017/ACOM:21. 1077 pp. (doi:ICES CM 2013/ACOM:13)

13. Dannevig A. 1933 On the age and growth of the cod (Gadus callarias L.) from the Norwegian Skagerrack coast. *Fisk. Skr. Ser. Havundersøkelser* **4**, 1–145.

14. Ruttenberg BI, Haupt AJ, Chiriboga AI, Warner RR. 2005 Patterns, causes and consequences of regional variation in the ecology and life history of a reef fish. *Oecologia* **145**, 394–403. (doi:10.1007/s00442-005-0150-0)

15. Ormseth OA, Norcross BL. 2009 Causes and consequences of life-history variation in North American stocks of Pacific cod. *ICES J. Mar. Sci.* **66**, 349–357.

16. Robertson DR, Ackerman JL, Choat JH, Posada JM, Pitt J. 2005 Ocean surgeonfish Acanthurus bahianus. I. The geography of demography. *Mar. Ecol. Prog. Ser.* **295**, 229–244.

17. Lilley RJ, Unsworth RKF. 2014 Atlantic Cod (Gadus morhua) benefits from the availability of seagrass (Zostera marina) nursery habitat. *Glob. Ecol. Conserv.* **2**, 367–377. (doi:10.1016/j.gecco.2014.10.002)

18. Tupper M, Boutilier RG. 1995 Effects of habitat on settlement, growth, and postsettlement survival of Atlantic cod (Gadus morhua). *Can. J. Fish. Aquat. Sci.* **52**, 1834–1841. (doi:10.1139/f95-176)