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Combined index for Greenland halibut in Sub 0+1 offshore

by

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Abstract

This document describes how a Delta-Lognormal Generalized Additive Model (Delta-GAM) was used to combine two survey time-series of trawl survey data for Greenland Halibut, in NAFO Subareas 0+1 (the shallow survey in 1A-F and the deep survey in 0A-1CD), to produce a standardized index of exploitable stock biomass. The main advantages of using this model rather than using separate area specific-indices are

1. Accounting for survey design changes: the model can incorporate changes in in survey design (e.g. the number of hauls per stratum, strata coverage, trawl positions, gear type), and includes uncertainties in the standardized index.

2. Handling missing data: the model "fills in" biomass estimated for missing strata and quantifies uncertainties associated with these imputations.

3. Integrated trend weighting: the model provides better weighting of trends between inshore and offshore area for overall stock trend.

4. Resolving potential conflicts in SPiCT: Potential different trends between inshore and offshore areas are integrated, avoiding conflicts in inputs to the SPiCT model.

Introduction

Stratified random bottom surveys have been carried out in NAFO Subareas 1A to 1F shallow waters (50- 600 m), from 1991 (Nygaard and Nogueira and in deep waters of NAFO Subareas 1CD (Nogueira and Estevez (2024) and 0A (Hedges, 2024), from 1997 from 1999 respectively (400-1500 m), with R/V Paamiut. In 2017, the R/V Paamiut was retired without the opportunity to conduct calibration experiments.

From 2018 to 2020, the shallow survey was conducted with chartered vessels of similar size, while the deep surveys were carried out with a chartered vessel in 2019. From 2022, the three surveys were carried out with a new research vessel R/V Tarajoq. An examination of gear performance found that these vessel changes had a minimal effect on trawl performance in the shallow survey (Nogueira and Treble 2020, Nogueira and Christiansen, 2023).

The shallow survey used a Skjervoy trawl until 2004, and Cosmos trawl since thereafter. The deep surveys used an Alfredo gear with RV Paamiut and the chartered vessel in 2019, but switched to Bacalao trawl with, RV Tarajoq.

We considered as exploitable biomass the individuals > 35 cm length.

Here we applied Delta-Lognormal Generalized Additive Model (Delta-GAM) to combine the two survey time-series (shallow and deep trawl survey data) for Greenland Halibut, in NAFO Subareas 0+1 offshore. This approach produced a standardized index of exploitable stock biomass which can be used as input in the SPiCT model

Material and Methods

Data source

We used catch, depth and distribution data for Greenland halibut from three buffered stratified random surveys: the shallow survey in 1A-F (Nygaard and Nogueira, 2023), the deep survey in 1CD (Nogueira and Estevez-Barcia, 2023) and the deep survey in 0A (Hedges, 2023). Figure 1 shows the distribution of the stations from both surveys.

The shallow survey in NAFO 1A-F covers the continental shelf from Cape Farewell in the south to latitude 72°30'N, including the Disko Bay. This survey spans depths of 50 - 600m and was conducted from 1991 to 2023 (no survey was conducted in 2021). Over this period, four vessels were used:

- 1991-2017: *R/V Paamiut*
- 2018: *C/V Sjurdarberg*
- 2019-2020: *C/V Helga Maria*
- 2022-2023: *R/V Tarajoq*

All vessels were of similar size, and used the same fishing gear (from 2005 onward), including door, trawl gear, and sensors, as well as consistent crew. Examination of gear parameters found that the effects of these vessel changes had a minimal effect on trawl performance (Nogueira and Treble 2020 and Nogueira and Christiansen, 2023). The survey used a Skjervoy gear until 2004, which was replaced by a Cosmos trawl in 2005 (Wieland and Bergström, 2005). Calibration experiments were conducted in the main shrimp areas in 2004 and 2005 and a formal analysis of conversion factors were established for shrimp (Rosing and Wieland, 2005). For this analysis, the index was estimated both with and without applying this calibration to the data.

The deep surveys in 1CD and 0A were conducted by Greenland and Canada respectively. However, given the common survey protocols (same vessels, gear, and sampling design), a combined index for 1CD and 0A was developed for the years when both surveys were conducted: 1999, 2001, 2004, 2008, 2012, 2014-2017 with RV Paamiut using an Alfredo trawl. In 2019, the combined index was also estimated with the CV Helga Maria data survey using the same Alfredo trawl, although this index was not comparable with the rest of the time-series. A new time series began in 2022-2023, with the new RV Tarajoq, and a new gear Bacalao, without the possibility of conducting calibration experiments between the 2 gears. No surveys were carried out in 2018, 2020 and 2021.

Before the analysis, raw catch data (kg/haul) were converted to density (kg/km2). The purpose of these analyses was to produce a combined index that could be used in the SPICT model (Pedersen and Berg, 2016). One of the assumptions for the SPiCT model is that the biomass refers to the exploitable part of the stock. To meet this assumption, we select only fish> 35 cm from the survey data. The numbers of fish were then converted to weight with the Length-Weight parameters.

The research survey in 1AF is performed in June and the deep surveys in 0A and 1CD are performed in autumn.

Statistical approach:

Survey indices are calculated using the methodology described in (Berg, Nielsen, and Kristensen 2014), with some key differences. Specifically, the response variable in this analysis is exploitable stock biomass rather than numbers-at-age, and we consider a broader class of equations describing the observed biomass in each haul. While Berg, Nielsen, and Kristensen 2014 assumed a time-invariant spatial effect, the model classes used here, contain space-time interactions, allowing for year-specific changes in the spatial distribution, and gear effects.

The space-time smoothers are decomposed into a high-resolution time-invariant spatial effect (f_1), and a lower resolution space-time interaction effect (f_2), where the latter captures random yearly deviations from the overall spatial distribution.

The following equation describes the model:

$$g(\mu_i) = Year(i) + Gear(i) + f_1(lon_i, lat_i) + f_2(Year_i, lon_i, lat_i) \\ + f_3(depth_i) + \log(sweptarea_i)$$

Where

$Year(i)$maps the ith haul to a categorical effect for each year,

$Gear(i)$ N is a random effect for the gear used in haul i ,

$f_1(lon_i, lat_i)$ is a 2-dimensional Duchon spline on the geographical coordinates (lon and lat)

$f_2(Year_i, lon_i, lat_i)$ is a 3-dimensional Duchon spline incorporating year, longitude, and latitude. This term allows for spatio-temporal interactions, capturing how spatial patterns may change over time. Year is treated as factor, i.e. an independent spatial effect is estimated for each year

$f_3(depth_i)$is a 1-dimensional Duchon spline for the effect of bottom depth.

$\log(sweptarea_i)$ is the offset for swept area, assuming catch is proportional to swept area (coefficient is fixed at 1).

The same model structure is used for both the presence/absence model and the conditional positive model. The model specification, written in R-syntax can be found in the appendix. The response variable is the amount of exploitable stock biomass (kg of fish larger than 35 cm). An offset is used for the effect of swept area effect ($\log(sweptarea_i)$), with its coefficient fixed at 1. This corresponds to the assumption that the catch is proportional to the swept area. All splines used for time, space and depth are Duchon splines with first derivative penalization. These splines distinguish themselves from conventional splines with second derivative penalization in that they do not follow linear trends beyond the data range; instead "go flat" similar to a random walk process.

In addition to the splines, fixed effects are incorporated to model differences in survey gear catchabilities. The function g varies between the two components of the model:

- the presence/absence model: the logit link function
- the conditional positive model: the identity link applied to the log-transformed response (i.e. lognormal distribution).

Once the parameters in the model are estimated, a standardized survey index is obtained by predicting and adding up the biomasses across a fine-meshed grid of points, consistent across all years. This is conceptually similar to conducting a virtual experiment where conditions such as the haul positions, and gear type remain identical in each year.

Preliminary analyses (not shown) investigated different error distributions (Delta-Lognormal, Delta-Gamma, and Tweedie). The Delta-Lognormal model showed the best performance based on the lowest Akaike Information Criterion (AIC) and the most satisfactory QQ-plots.

The model is estimated using three variations of input data:

1. SI: Raw input data used and model equation, including estimation of gear effects.

2. SI.nogear: the conversion factor between old and new shallow survey gears (Skjervoy versus Cosmos) applied to response variable prior to modelling, no additional estimation of gear effects included.

3. SI.con: the conversion factor between old and new shallow survey gears (Skjervoy versus Cosmos) applied to response variable prior to modelling, also estimation of gear effects included.

Results and discussion

Table 1 presents the number of hauls by year and gear type. The "Cosmos" and "Skjervoy" gears were employed in shallow inshore survey, while the "Alfredo" and "Bacalao"gears were used in the offshore deep-water surveys. Overlapping survey years between "Skjervoy" and "Alfredo", between "Cosmos" and "Alfredo", and finally between "Cosmos" and "Bacalao", allowed the estimation of gear effects.

We created the prediction grid (Figure 2) to define the spatial framework for biomass predictions.

Table 2 shows the number of positive hauls taken between 400 and 600 meters depth (the range of overlap) by gear type. A much higher proportion of zero catches was observed for "Cosmos" and "Skjervoy", corroborating the model estimates. The higher proportion of zeroes with shallow-water gears is not solely due to lower Greenland halibut densities in the shallow areas but also reflects differences in gear efficiency.

- SI (Selected Model): Includes gear effects without applying conversion factors to shallow-survey data. This model achieved the best AIC and was selected for the final analysis.
- SI.nogear: Excludes gear effects, resulting in overestimation until 2004, underestimation from 2005 to 2021, and renewed overestimation after the introduction of the new vessel.

- SI.con: Applies conversion factors to shallow survey data but yields results similar to the SI model.

We kept the SI model based on the best AIC that includes the gear effect and unconverted shallow-survey data.

Figure 4 illustrated

1) The distribution of the survey index across depth intervals (100 m bin),

2) A smooth density curve of biomass predictions at varying depths and

3) The mean value of the survey index by bin.

Most biomass was concentrated at depths >800 m, peaking between 1000–1200 m. The mean depth of biomass distribution remained relatively stable over the years.

The combined model gives stable and consistent estimates of the gear effects and biomass indices.

Residuals were approximately normally distributed (Figures 5-6). The QQ plot showed minor deviations from normality. Modelling residuals as a smooth function of the swept area revealed no substantial trends, suggesting no systematic relationship between residuals and swept area.

Spatial residuals, biomass distributions, and uncertainties are presented in Figures 7-10. Most of the biomass was located on the slopes of 1CD and 0A. Higher uncertainty in predictions was observed in shallow strata

(0A and 1A-F) until 2004, with uncertainty decreasing after 2005. Spatial patterns showed no significant trends across the study area.

The old “Skjervoy” gear was estimated to catch approximately 0.6 times as much as the new “Cosmos” gear. Deep-water gears (“Alfredo” and “Bacalao”) had similar efficiencies, but their probability of a non-zero catch was substantially higher compared to shallow-water gears (Figure 11).

The combined biomass index increased from 1991 to 2005 and has since remained stable, with minor fluctuations.

Retrospective analysis showed good consistency, with Mohn’s rho = 0.045, indicating no systematic biases or trends were observed in biomass estimates across years.

Conclusions:

This study assessed the effects of gear type on biomass estimates of Greenland halibut, integrating data from shallow and deep-water surveys. The selected model (SI), which includes gear effects without conversion of shallow-survey data, provided the best fit based on AIC and produced consistent biomass indices.

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Wieland, K.,& M. Storr-Paulsen, 2006: Effect of tow duration on catch rates and mean length of Northern shrimp (Pandalus borealis) and Greenland halibut (Reinhardtius hippoglossoides) in the West Greenland Bottom Trawl Survey. Fish. Res. 78: 276-285

Tables and figures:

Table 1. Number of hauls by year and gear. Cosmos and Skjervoj gears are from the shallow survey in 1AF and Alfredo and Bacalao are from the deep surveys in 0A and 1CD.

	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003
Cosmos	0	0	0	0	0	0	0	0	0	0	0	0	0
Skjervoy	166	169	161	155	172	157	174	215	227	211	229	217	190
Alfredo	0	0	0	0	0	0	0	0	92	0	85	0	0
Bacalao	0	0	0	0	0	0	0	0	0	0	0	0	0

	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016
Cosmos	0	205	231	248	246	261	277	194	201	196	206	208	180
Skjervoy	201	0	0	0	0	0	0	0	0	0	0	0	0
Alfredo	106	0	0	0	144	0	143	0	123	0	141	143	146
Bacalao	0	0	0	0	0	0	0	0	0	0	0	0	0

	2017	2018	2019	2020	2022	2023
Cosmos	228	206	183	232	307	254
Skjervoy	0	0	0	0	0	0
Alfredo	127	0	142	0	0	0
Bacalao	0	0	0	0	92	141

Table 2. Number of positive hauls taken between 400 and 600 meters depth (the range of overlap) by gear type.

	FALSE	TRUE
Cosmos	156	378
Skjervoy	56	387
Alfredo	9	178
Bacalao	2	27

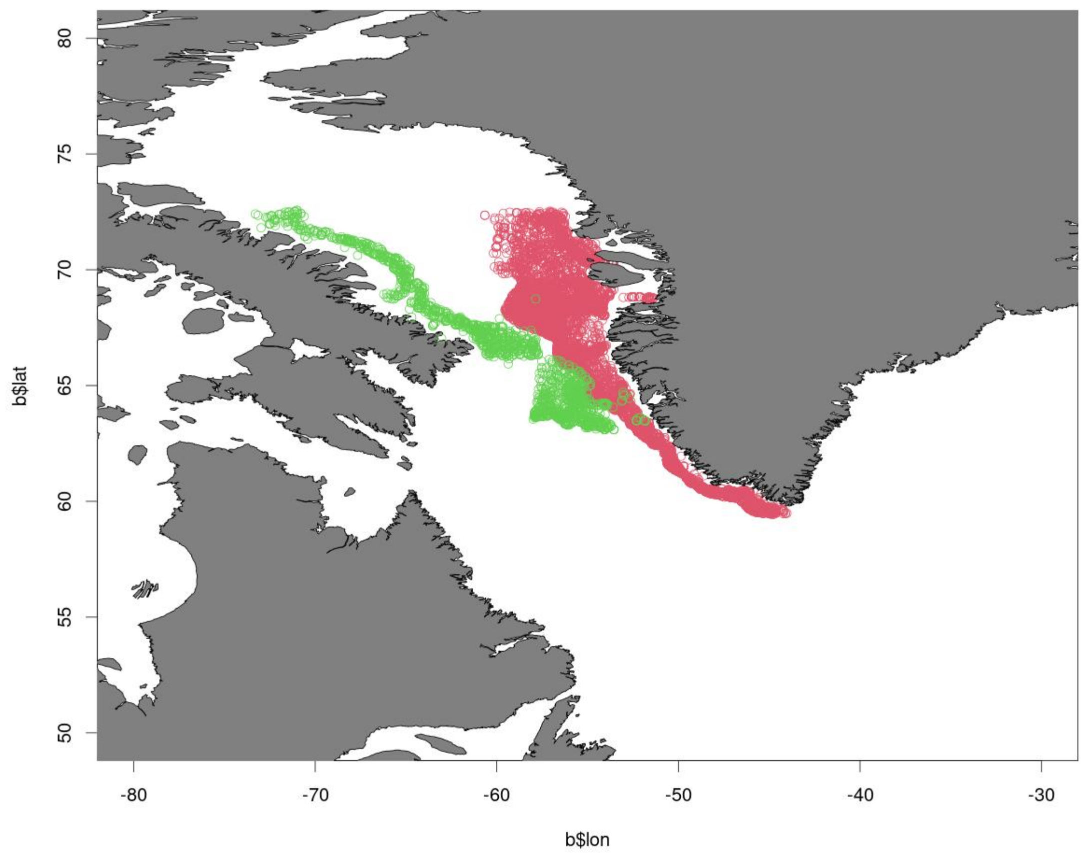

Figure 1. Input data: Trawl positions (red = shallow survey in 1AF, green = deep survey in 0A-1CD)

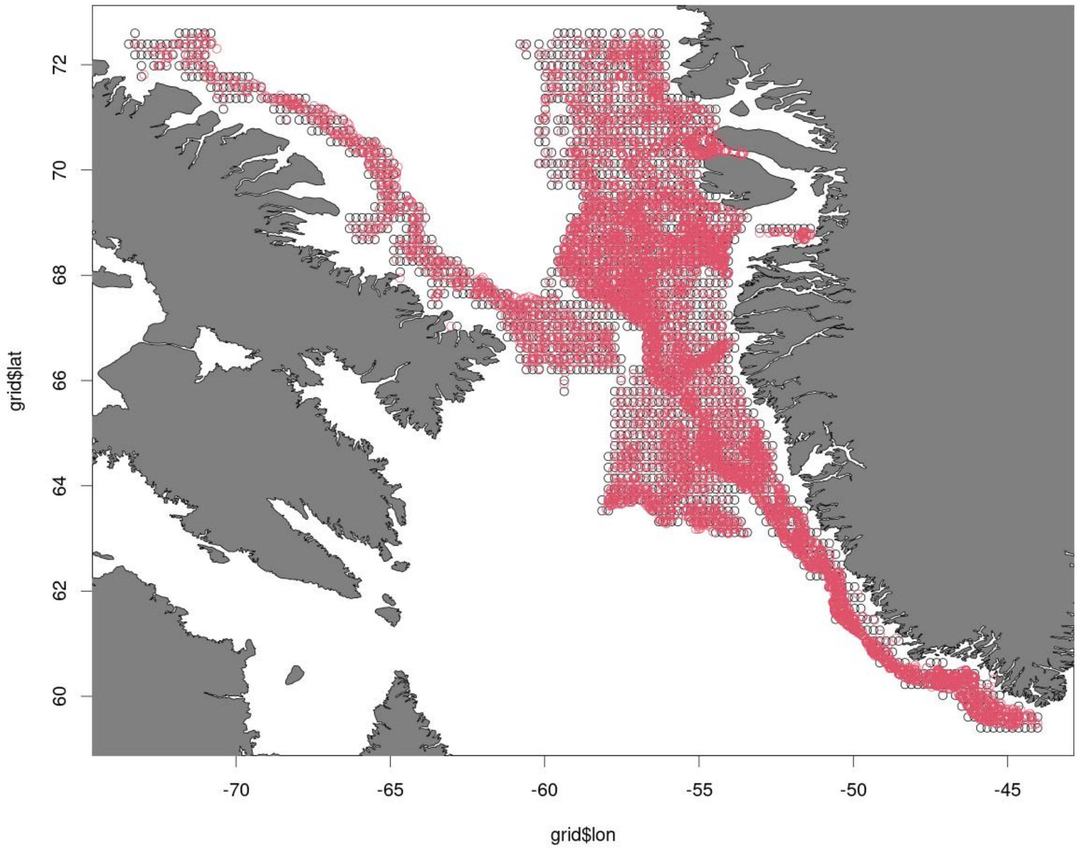

Figure 2. Prediction grid (black) and actual trawl positions (red).

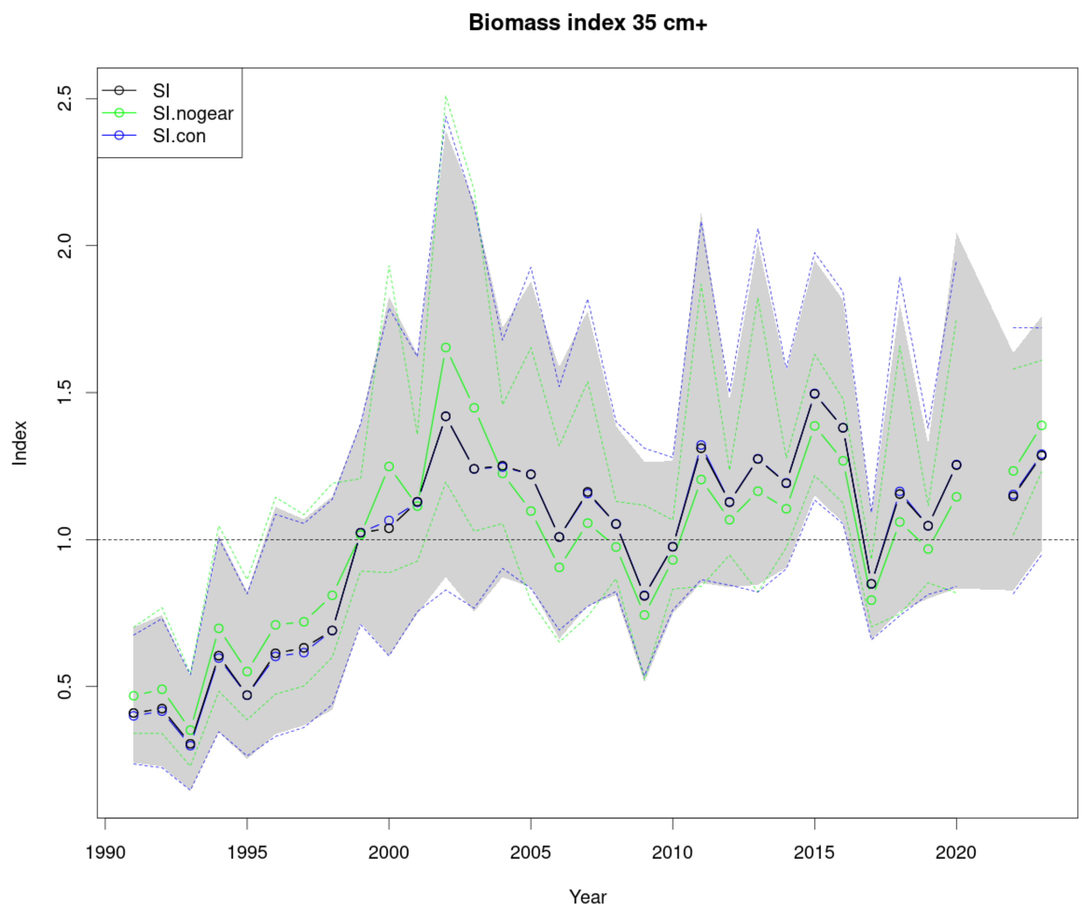

Figure 3. Comparison of indices. SI: model-based gear effect, no prior conversion factor. SI.nogear: no gear effect, prior conversion factor applied. SI.con: model-based gear effect, prior conversion factor applied.

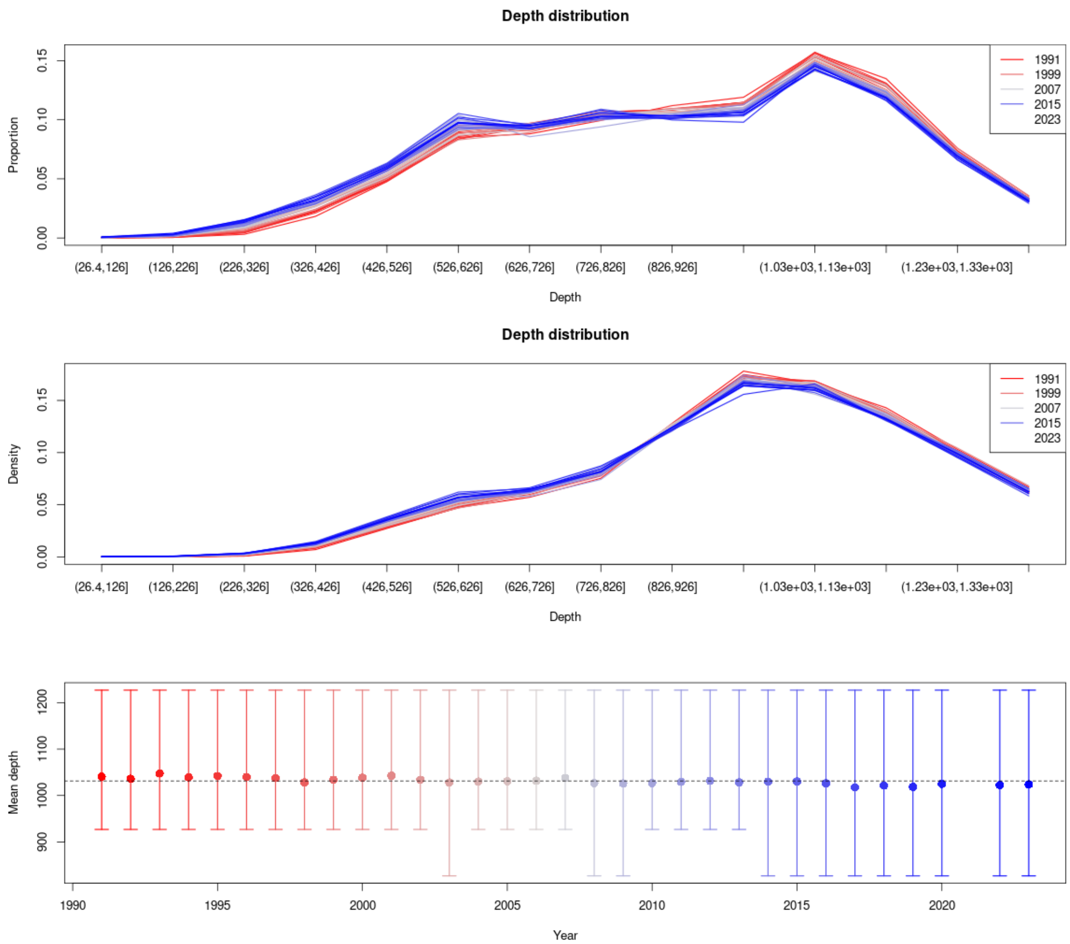

Figure 4. Depth distribution.

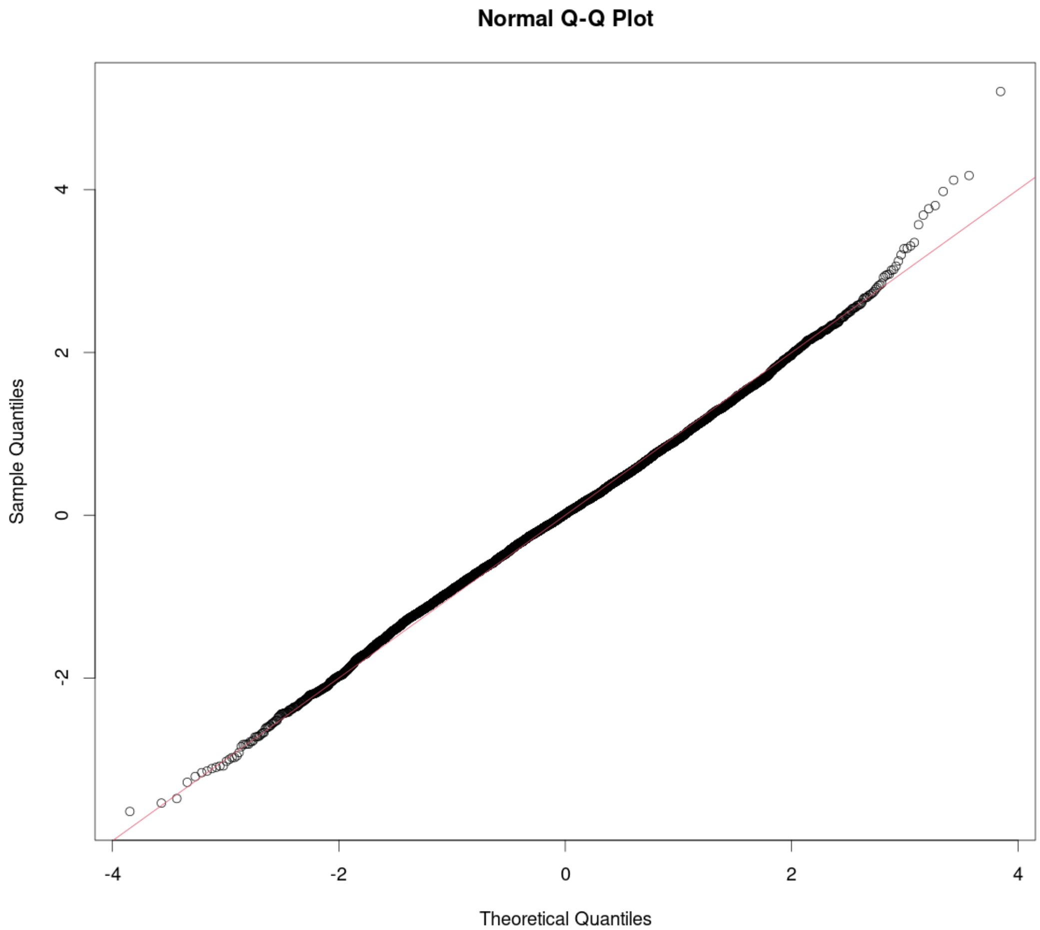

Figure 5. Residual QQ-plot.

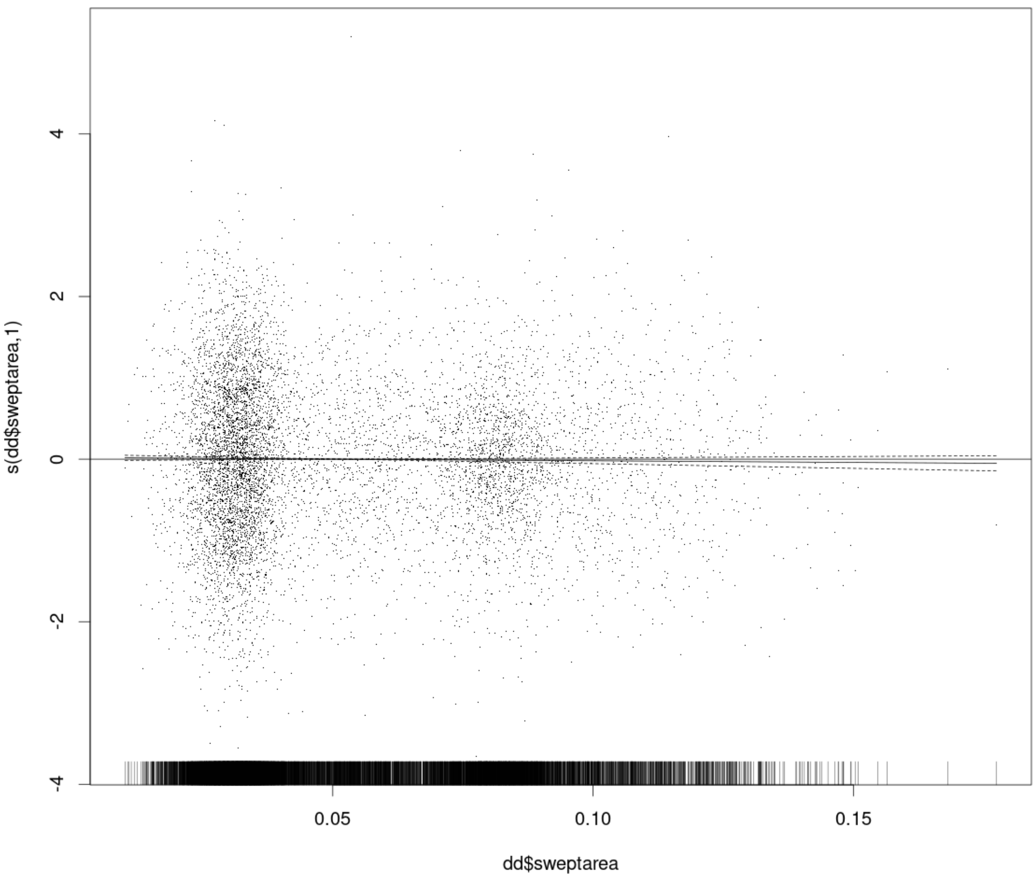

Figure 6. Residuals versus swept area.

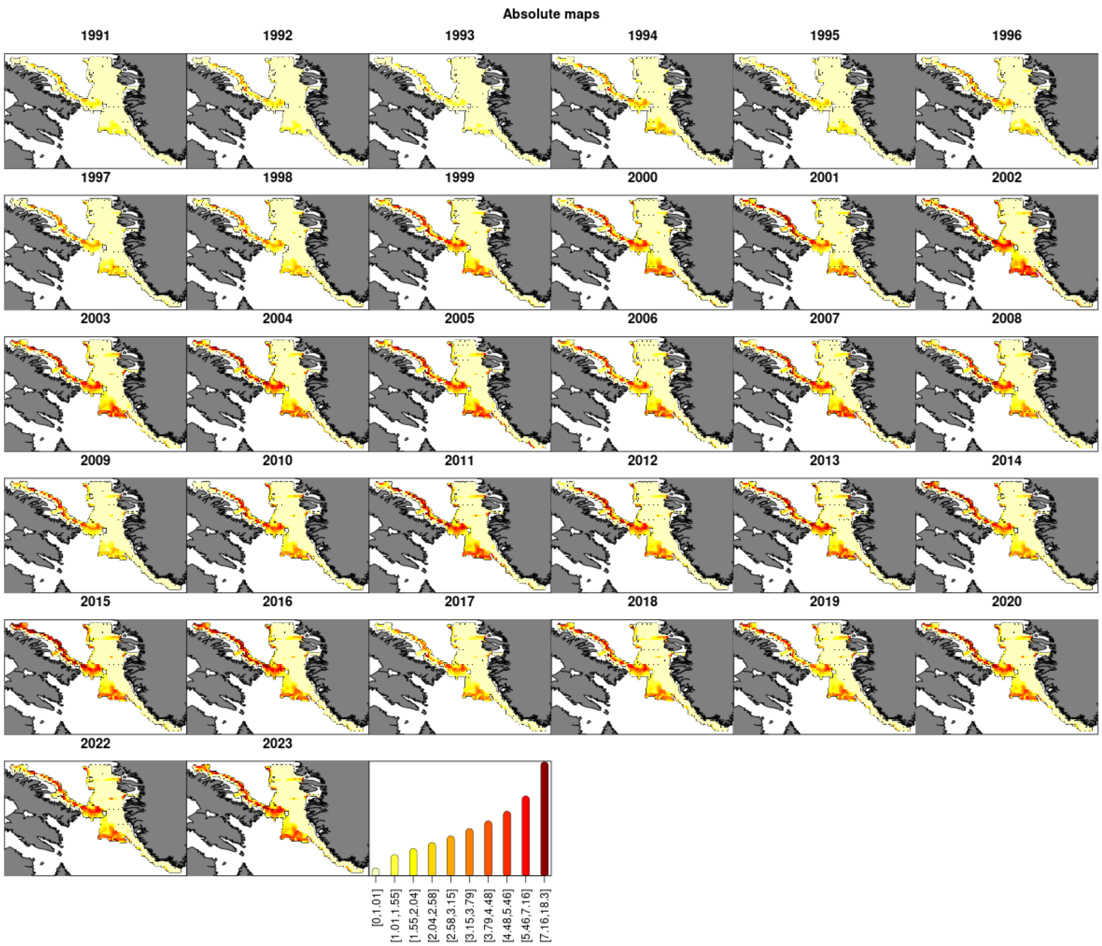

Figure 7. Estimated distribution maps.

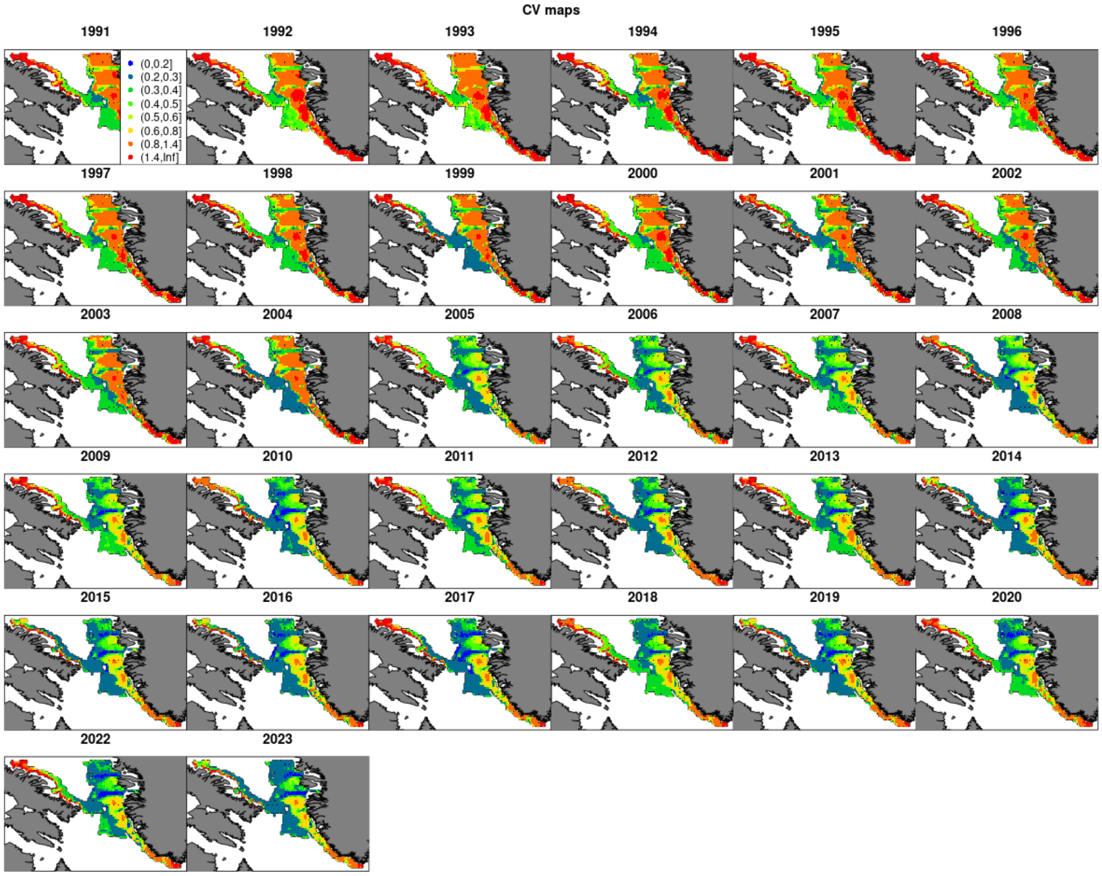

Figure 8. Uncertainty maps (CV).

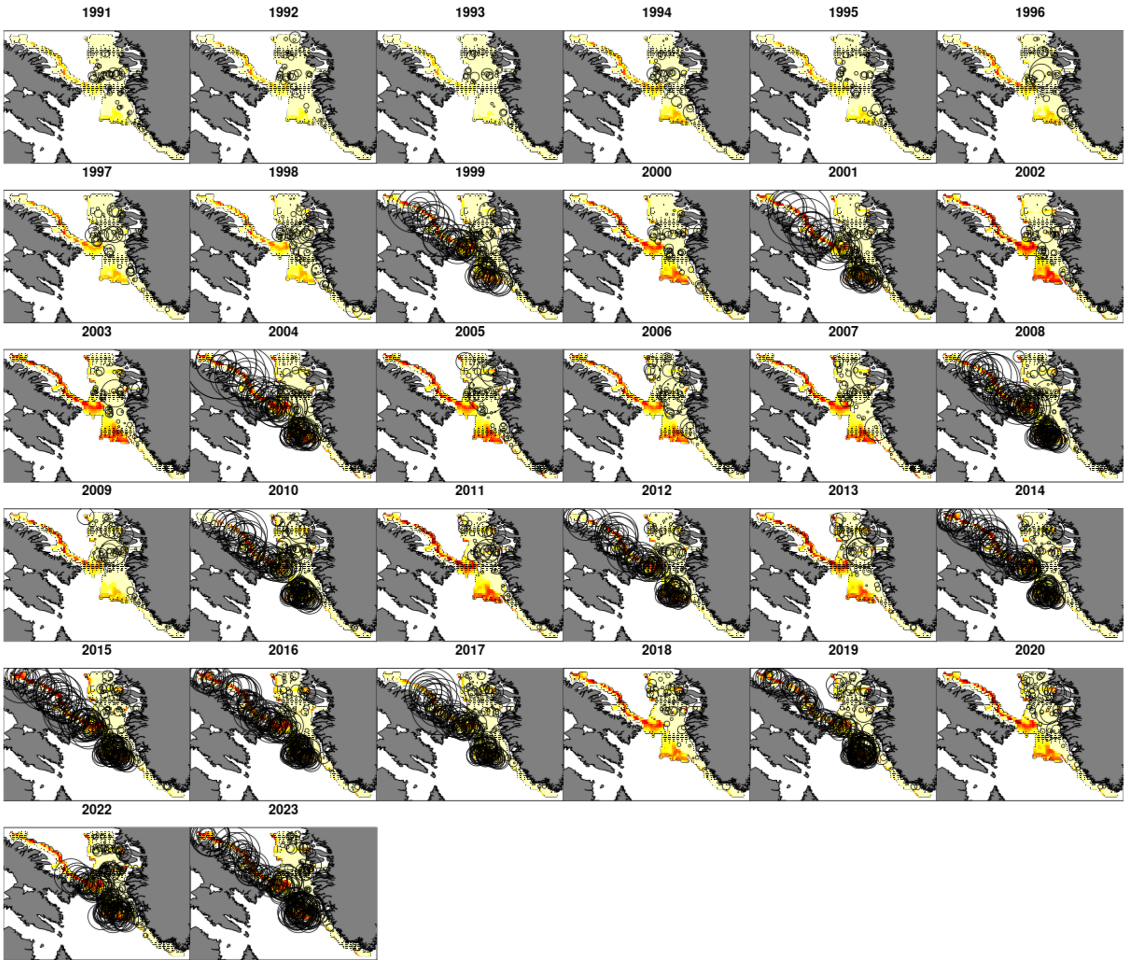

Figure 9. Estimated distribution maps - bubble size proportional to observed catches.

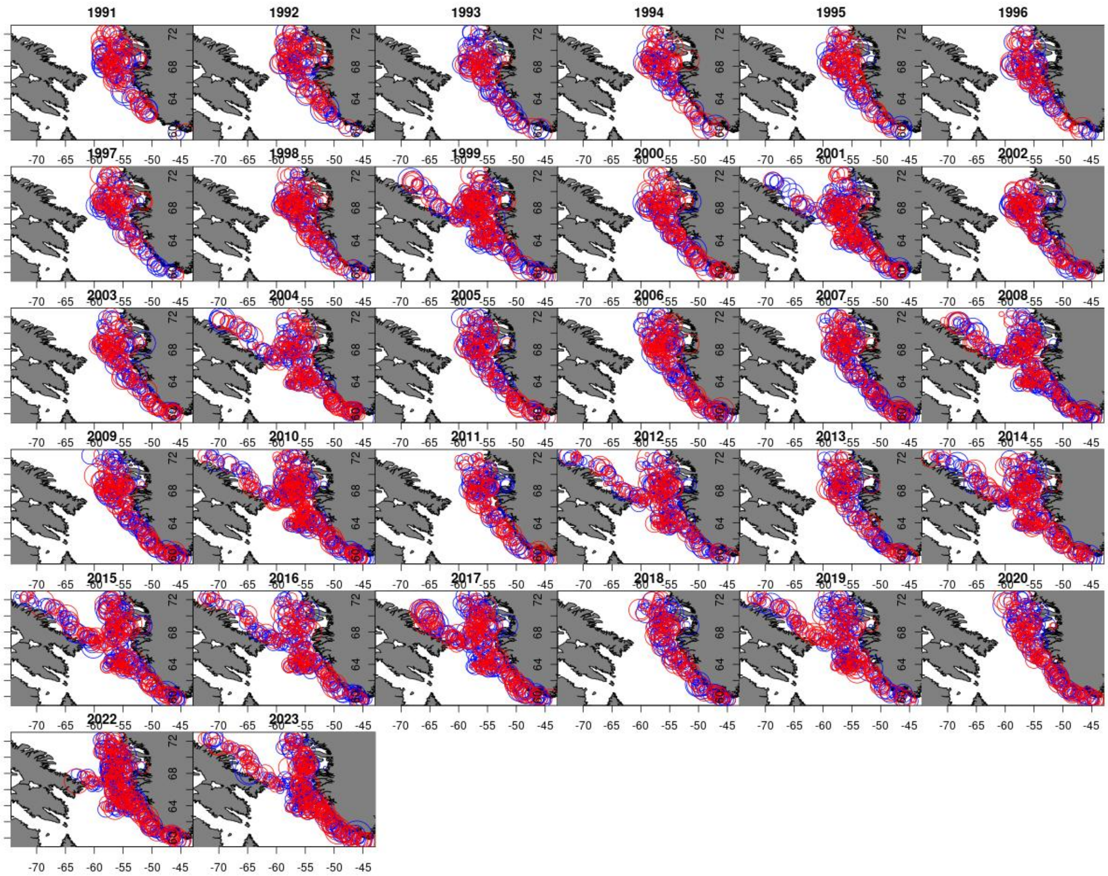

Figure 10. Spatial residuals.

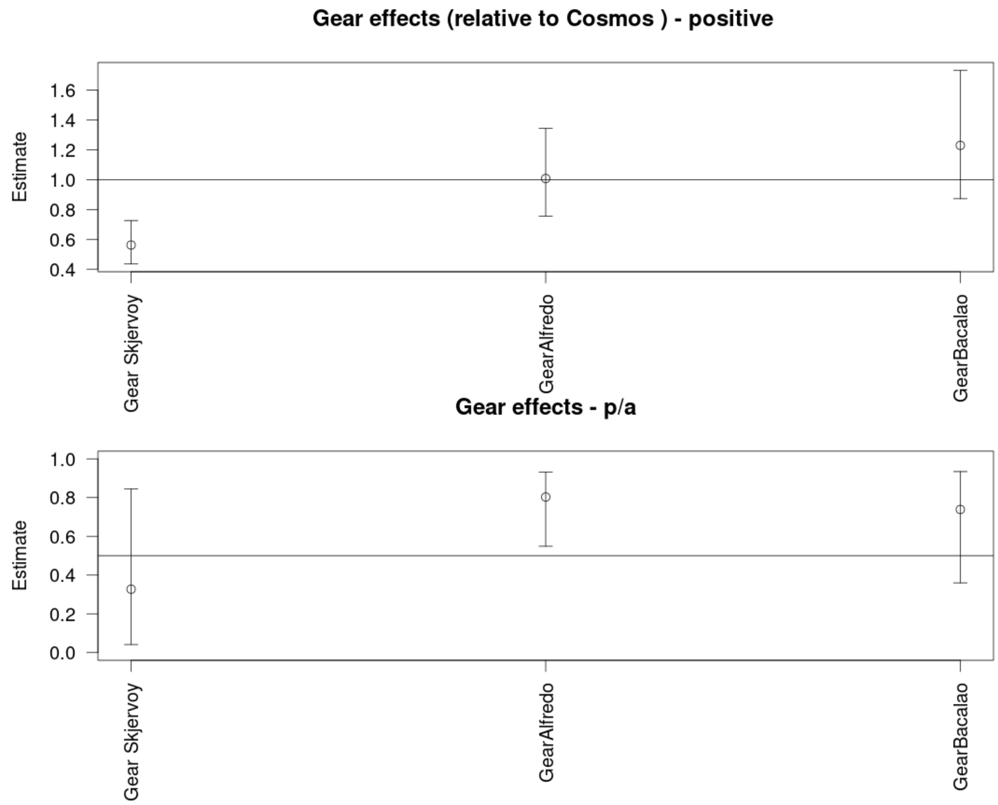

Figure 11. Estimated gear effects for model with no prior gear conversion. Top: conditional positive model, bottom: presence/absence model.

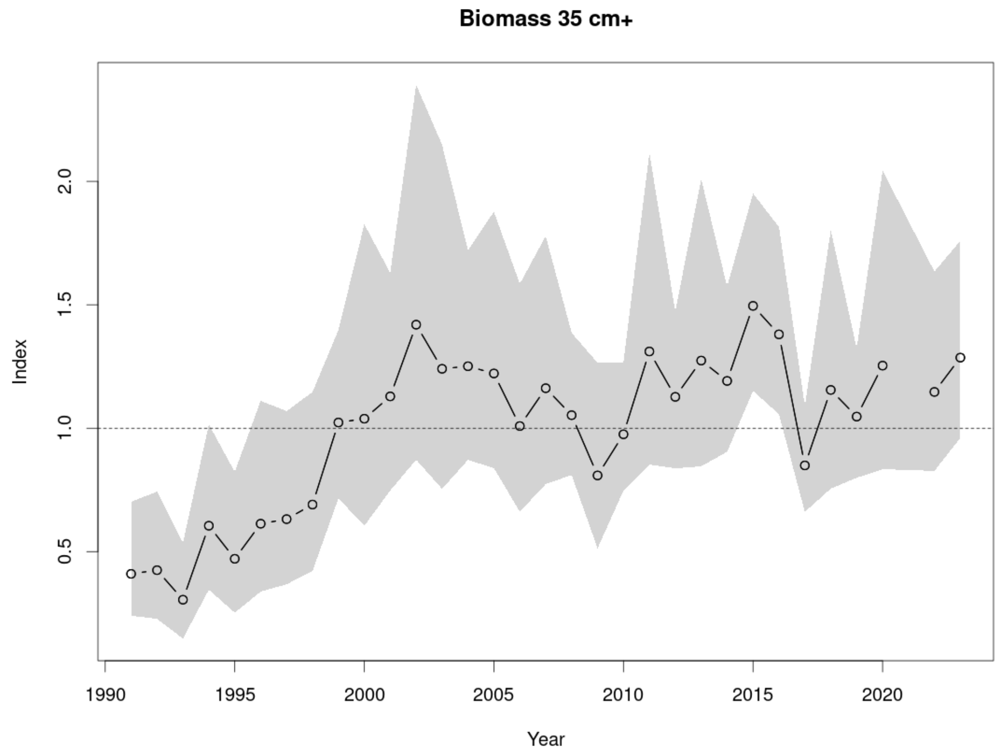

Figure 12. Estimated biomass index (rescaled to mean 1). Grey shaded area indicates 95% confidence interval.

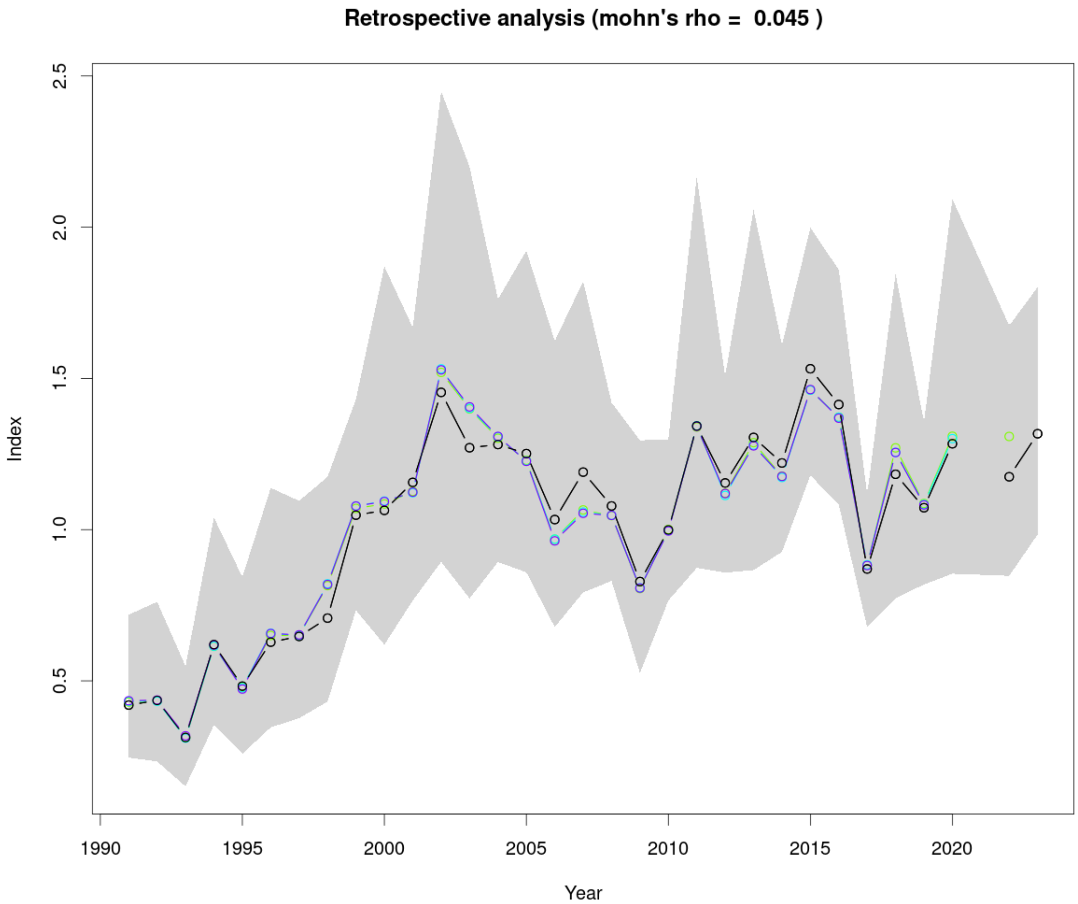

Figure 13. Retrospective analysis.

Appendix

Model summary - conditional positive

```
Family: gaussian
Link function: identity

Formula:
log(A1) ~ Year + Gear + s(sqrt(Depth), k = 6, bs = "ds", m = c(1,
    0)) + s(lon, lat, bs = "ds", m = c(1, 0.5), k = 200) + s(lon,
    lat, bs = "ds", m = c(1, 0.5), by = Year, k = 12, id = 1) +
    offset(log(sweptarea))

Parametric coefficients:
              Estimate Std. Error t value Pr(>|t|)
(Intercept)   4.383404   0.183794  23.850  < 2e-16 ***
Year1992      0.044635   0.174492   0.256 0.798120
Year1993     -0.244132   0.188923  -1.292 0.196366
Year1994      0.349566   0.174277   2.006 0.044957 *
Year1995      0.128542   0.178370   0.721 0.471176
Year1996      0.430027   0.184679   2.329 0.019944 *
Year1997      0.427494   0.171989   2.486 0.012982 *
Year1998      0.564827   0.161399   3.500 0.000472 ***
Year1999      0.862963   0.142987   6.035 1.76e-09 ***
Year2000      0.881137   0.170660   5.163 2.57e-07 ***
Year2001      0.857487   0.146289   5.862 5.03e-09 ***
Year2002      1.175732   0.165829   7.090 1.63e-12 ***
Year2003      1.084940   0.168075   6.455 1.24e-10 ***
Year2004      1.059312   0.147025   7.205 7.13e-13 ***
Year2005      1.081165   0.208792   5.178 2.37e-07 ***
Year2006      0.885698   0.209684   4.224 2.46e-05 ***
Year2007      1.017270   0.213823   4.758 2.04e-06 ***
Year2008      0.919256   0.172907   5.316 1.13e-07 ***
Year2009      0.675413   0.212316   3.181 0.001480 **
Year2010      0.979030   0.171516   5.708 1.24e-08 ***
Year2011      1.172884   0.216527   5.417 6.49e-08 ***
Year2012      0.994795   0.173880   5.721 1.15e-08 ***
Year2013      1.134619   0.217104   5.226 1.84e-07 ***
Year2014      0.922994   0.172186   5.360 8.86e-08 ***
Year2015      1.133263   0.171727   6.599 4.78e-11 ***
Year2016      1.107813   0.173297   6.393 1.86e-10 ***
Year2017      0.797861   0.172024   4.638 3.65e-06 ***
Year2018      1.041749   0.221381   4.706 2.63e-06 ***
Year2019      0.970250   0.172193   5.635 1.90e-08 ***
Year2020      1.102097   0.214045   5.149 2.77e-07 ***
Year2022      1.092211   0.196762   5.551 3.06e-08 ***
Year2023      1.087487   0.199993   5.438 5.78e-08 ***
Gear Skjervoy -0.576970  0.128239  -4.499 7.05e-06 ***
GearAlfredo   0.007753   0.143646   0.054 0.956958
GearBacalao   0.206693   0.171712   1.204 0.228783
```

```
---
Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Approximate significance of smooth terms:
                            edf  Ref.df       F   p-value
s(sqrt(Depth))            4.969       5 319.971  < 2e-16 ***
s(lon,lat)              138.561     199   6.144  < 2e-16 ***
s(lon,lat):Year1991       1.449      11   0.164  0.25288
s(lon,lat):Year1992       1.315      11   0.368  0.01612 *
s(lon,lat):Year1993       1.070      11   0.331  0.01185 *
s(lon,lat):Year1994       1.262      11   0.455  0.00377 **
s(lon,lat):Year1995       1.339      11   0.320  0.02809 *
s(lon,lat):Year1996       1.266      11   0.112  0.39213
s(lon,lat):Year1997       1.428      11   0.082  0.63985
s(lon,lat):Year1998       1.874      11   0.324  0.07904 .
s(lon,lat):Year1999       3.461      11   0.109  0.93667
s(lon,lat):Year2000       1.742      11   0.410  0.02703 *
s(lon,lat):Year2001       3.384      11   0.945  0.00147 **
s(lon,lat):Year2002       1.838      11   0.212  0.23808
s(lon,lat):Year2003       1.808      11   0.171  0.34816
s(lon,lat):Year2004       3.675      11   0.384  0.23281
s(lon,lat):Year2005       1.945      11   0.350  0.06939 .
s(lon,lat):Year2006       1.839      11   0.203  0.25979
s(lon,lat):Year2007       1.720      11   0.558  0.00560 **
s(lon,lat):Year2008       3.836      11   0.643  0.03297 *
s(lon,lat):Year2009       1.712      11   0.567  0.00476 **
s(lon,lat):Year2010       3.987      11   0.600  0.05664 .
s(lon,lat):Year2011       1.549      11   0.095  0.60590
s(lon,lat):Year2012       3.636      11   0.299  0.40336
s(lon,lat):Year2013       1.488      11   0.091  0.60405
s(lon,lat):Year2014       3.881      11   0.647  0.03030 *
s(lon,lat):Year2015       4.018      11   0.931  0.00313 **
s(lon,lat):Year2016       3.933      11   0.442  0.17360
s(lon,lat):Year2017       3.710      11   1.027  0.00111 **
s(lon,lat):Year2018       1.406      11   0.347  0.02510 *
s(lon,lat):Year2019       3.959      11   1.758 1.22e-06 ***
s(lon,lat):Year2020       1.667      11   0.175  0.29306
s(lon,lat):Year2022       3.089      11   0.562  0.03190 *
s(lon,lat):Year2023       3.959      11   0.560  0.06477 .
---
Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

R-sq.(adj) = 0.825   Deviance explained = 80.2%
-ML = 4560.8  Scale est. = 0.6348   n = 3631
```

Model summary - presence/absence

```
Family: binomial
Link function: logit
```

```
Formula:
A1 > 0 ~ Year + Gear + s(sqrt(Depth), k = 6, bs = "ds", m = c(1,
    0)) + s(lon, lat, bs = "ds", m = c(1, 0.5), k = 150) + s(lon,
    lat, bs = "ds", m = c(1, 0.5), by = Year, k = 8, id = 1) +
    offset(log(sweptarea))

Parametric coefficients:
              Estimate Std. Error z value Pr(>|z|)
(Intercept)    2.42023    1.24877   1.938  0.05261 .
Year1992      -0.95640    0.41983  -2.278  0.02272 *
Year1993      -0.98502    0.43709  -2.254  0.02422 *
Year1994      -0.21953    0.43023  -0.510  0.60987
Year1995      -0.63492    0.42828  -1.482  0.13821
Year1996      -0.30483    0.42872  -0.711  0.47707
Year1997       0.08970    0.42360   0.212  0.83230
Year1998       0.49391    0.38350   1.288  0.19778
Year1999       0.60321    0.37020   1.629  0.10322
Year2000       0.41422    0.37439   1.106  0.26856
Year2001       0.27894    0.36439   0.765  0.44398
Year2002       1.06597    0.37119   2.872  0.00408 **
Year2003       1.23751    0.38596   3.206  0.00134 **
Year2004       0.90375    0.36683   2.464  0.01375 *
Year2005       0.76260    1.26398   0.603  0.54629
Year2006       0.40665    1.26592   0.321  0.74804
Year2007       0.17772    1.26643   0.140  0.88840
Year2008       0.20755    1.25209   0.166  0.86835
Year2009      -0.10781    1.26600  -0.085  0.93214
Year2010      -0.02918    1.24198  -0.023  0.98125
Year2011       0.46187    1.27260   0.363  0.71665
Year2012      -0.05518    1.25346  -0.044  0.96488
Year2013       0.16530    1.27393   0.130  0.89676
Year2014       0.43571    1.26073   0.346  0.72964
Year2015       0.46113    1.25905   0.366  0.71417
Year2016       0.63300    1.26147   0.502  0.61581
Year2017       0.51137    1.26291   0.405  0.68554
Year2018       0.51040    1.27832   0.399  0.68969
Year2019       0.60700    1.25938   0.482  0.62982
Year2020       0.44109    1.27347   0.346  0.72907
Year2022       0.47331    1.26554   0.374  0.70840
Year2023       0.81524    1.26934   0.642  0.52071
Gear Skjervoy -0.72102    1.20887  -0.596  0.55088
GearAlfredo    1.40488    0.60480   2.323  0.02019 *
GearBacalao    1.03860    0.80769   1.286  0.19848
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Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Approximate significance of smooth terms:
                   edf Ref.df  Chi.sq p-value
s(sqrt(Depth))   4.739      5 784.238  <2e-16 ***
s(lon,lat)      85.230    149 593.508  <2e-16 ***
```

```
s(lon,lat):Year1991      2.472             7      20.475   2.26e-07   ***
s(lon,lat):Year1992      2.271             7       2.557   0.289666
s(lon,lat):Year1993      2.160             7      10.193   0.000690   ***
s(lon,lat):Year1994      2.400             7       6.902   0.013122   *
s(lon,lat):Year1995      2.363             7       4.306   0.090993   .
s(lon,lat):Year1996      2.407             7       5.601   0.036021   *
s(lon,lat):Year1997      2.454             7       8.882   0.003158   **
s(lon,lat):Year1998      2.812             7      11.809   0.000586   ***
s(lon,lat):Year1999      3.118             7      10.644   0.001956   **
s(lon,lat):Year2000      2.951             7       8.669   0.007218   **
s(lon,lat):Year2001      3.281             7       4.010   0.226695
s(lon,lat):Year2002      2.912             7      10.158   0.002244   **
s(lon,lat):Year2003      2.749             7       4.908   0.086385   .
s(lon,lat):Year2004      3.207             7       7.967   0.014499   *
s(lon,lat):Year2005      3.076             7       4.358   0.160239
s(lon,lat):Year2006      3.010             7       2.638   0.427356
s(lon,lat):Year2007      2.989             7       6.168   0.044322   *
s(lon,lat):Year2008      3.368             7       1.826   0.726491
s(lon,lat):Year2009      3.029             7       5.841   0.059067   .
s(lon,lat):Year2010      3.926             7      18.387   9.40e-06   ***
s(lon,lat):Year2011      2.741             7       2.863   0.333737
s(lon,lat):Year2012      3.421             7      11.265   0.001279   **
s(lon,lat):Year2013      2.670             7       1.608   0.651571
s(lon,lat):Year2014      3.078             7      10.512   0.001886   **
s(lon,lat):Year2015      3.141             7      11.067   0.001325   **
s(lon,lat):Year2016      2.949             7      10.328   0.001642   **
s(lon,lat):Year2017      2.961             7       8.059   0.010994   *
s(lon,lat):Year2018      2.570             7      17.300   6.20e-06   ***
s(lon,lat):Year2019      3.221             7       5.190   0.101537
s(lon,lat):Year2020      2.704             7      11.144   0.000777   ***
s(lon,lat):Year2022      3.105             7      18.773   5.26e-06   ***
s(lon,lat):Year2023      3.183             7      34.320    <  2e-16   ***
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Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

R-sq.(adj) =  0.701   Deviance explained = 62.5%
-ML =  2232  Scale est. = 1     n = 8332
```