Version: 20/11/2025

An assessment of cod in the Firth of Clyde

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Executive summary

1. At present Clyde cod are assessed by ICES as part of the Northwestern substock that includes part of the North Sea and all of the West of Scotland. Clyde cod are, however, considered to be a substock separate from the West of Scotland and may have different dynamics. This document reports an assessment of cod in the Clyde as a single stock unit.
2. Data available include a time series of total landings and discards from 1985-2019 based on sampling by the Scottish Government's Marine Directorate. These data include age compositions for some years. In addition, research vessel surveys provide an index of abundance as well age compositions for the whole period. The level of sampling is generally low and there are gaps in some time series, but data are sufficient to perform a full stock assessment.
3. An age structured stock assessment model is developed that can estimate stock biomass and fishing mortality despite the data gaps. Sensitivity analysis and retrospective analysis suggest the assessment is robust to a variety of assumptions about the data and the fishery.
4. A surplus production model that makes different assumptions about the stock population dynamics is developed and applied to the catch and survey data. The results from this model are very similar to the age structured model which suggests the results are not sensitive to model structure.
5. The assessment estimates very high rates of fishing mortality and a substantial decline in spawning stock biomass. Currently, the high rates of fishing are attributable to bycatch of cod in the *Nephrops* fishery.
6. Estimates of Maximum Sustainable Yield (MSY) derived from the assessment show that the spawning stock biomass is less than 10% of the biomass expected at MSY. The stock appears to have collapsed around the year 2000. Fishing mortality from 2001-2014 was at or exceeded values that would be expected to

cause stock collapse (F_{crash}). Current fishing mortality (as of 2019) is close to F_{crash}.

7. Investigating the productivity of the stock (the number of recruits produced per tonne of spawning biomass) shows that the current productivity is within the historical range and above rates in the mid-1980s. It does not appear that stock decline is the result of impaired productivity.
8. The most likely cause of the failure of the stock to recover is the high rate of fishing resulting from the bycatch in the *Nephrops* trawl fishery. Stock recovery needs to focus on measures to reduce bycatch, perhaps by changing gear design. Enhancing productivity through the protection of spawning behaviour is unlikely to be successful at current rates of exploitation.

Introduction

The cod population in the Clyde was for many years included in the assessment covering the whole of ICES Division 6a (West of Scotland). This assessment estimated that the fishing mortality was persistently high and spawning stock biomass (SSB) in the area had declined to a point where the fishing for cod was effectively closed (ICES 2022a). More recently Clyde cod has been included in the “Northwestern” subpopulation of cod that includes 6a and the northern part of North Sea (part of ICES Division 4a). The Northwestern substock is now assessed as a component of the Northen shelf cod. This assessment indicates that the Northwestern substock SSB recovered more than 10 years earlier than was estimated in the last 6a cod assessment and that the fishing mortality had declined substantially in recent years (ICES 2024). The radical change in the perceived state of the stock is an indication of the uncertainty in the assessment of cod in this area (Cook, 2019a). Furthermore, the assessment area is so large that data from Division 4a (North Sea) influence the analysis and hence understanding the status of cod in the Clyde is masked by events in the wider assessment unit. The ICES assessments cannot provide a reliable indicator of the status of cod in the Clyde.

Recent analysis has suggested that there is evidence that cod in the Clyde comprise a separate subpopulation (ICES 2022b). In addition, there is evidence that the Clyde ecosystem is in a poor state (Thurston and Roberts; 2010, Heath and Speirs; 2011, McIntyre et al; 2012) and that fish stocks, including cod, are depleted. It seems likely that the optimistic Northwestern subpopulation stock status may not reflect the situation for cod in the Clyde. Indeed, there are specific conservation measures applying to the Clyde fishery such as a ban on directed trawling for whitefish, and a spawning area closure to protect cod, that reflect the belief that the stock is in a poor state.

A recent stock assessment of cod in the Clyde found that the SSB appears to be at a very low level while the exploitation rate is very high (Adão, 2025). The assessment uses research vessel data and discard data from the *Nephrops* trawl fleet that takes a bycatch of cod. Since the analysis was undertaken additional historical data have become available that includes total landings and discards by fleet and associated age compositions for the landed component. This report updates the earlier assessment model to include these data and investigates the robustness of the assessment. The state of the stock in relation to Maximum Sustainable Yield (MSY) is evaluated.

Data

The available data collected by the Scottish Government's Marine Directorate (formerly Fisheries Research Services and Marine Scotland Science) are summarised in Figure 1. Commercial catches are available by fleet (effectively gear type) and have been grouped into two "fleets" comprising the *Nephrops* trawl fleet and "Other gears". The latter is dominated by light trawl and seine and is treated in the analysis as a single fleet. *Nephrops* trawl, seine and light trawl account for 95% of the reported landings.

The catch data are disaggregated into landings and discards. Total landed weight was taken from officially recorded landings for the ICES rectangles 39E4,39E5, 40E4 and 40E5. Total discarded weight by *Nephrops* trawlers for the period 2002-2019 is taken from Adão (2025) using observer trip data. The estimates are based on the ratio of cod bycatch to *Nephrops* landings per trip raised by annual weight of *Nephrops* landed. For this fleet, in the period 1990-2001, discarded weight was estimated as the mean discarded weight per trip raised by the number of trips using the time series model in Adão (2025). The latter model gives very similar values to the ratio estimator. For the discarded weight by other gears, the proportion discarded reported in Fernandes *et al* (2011) was applied to the reported landings in the Clyde by all gears excluding *Nephrops* trawl.

Age compositions are available for the landings for most years until they ceased around 2007 (Appendix F). For discards, age compositions are only available for 2002 onwards for the *Nephrops* trawl fleet as estimated by Adão (2025).

In addition to fishery catch data, annual trawl surveys have been conducted in ICES Division 6a that include sampling stations in the Clyde. For these surveys both relative abundance (catch numbers per hour) and associated age compositions are available (Adão, 2025). The raw data were obtained from the ICES website (https://datras.ices.dk/Data_products/Download/Download_Data_public.aspx). Two surveys are conducted, one in quarter 1 and the other in quarter 4. The time series is affected by a change of survey design in 2011. Since the survey design can affect sampling efficiency, each survey is split into two at the point when the design changed leading to four surveys for modelling purposes. Tables of the age compositions, abundance indices and catches are given in Appendix A (Table A 1-Table A 6) and Table D1.

Weights at age were available for landings, discards and the surveys. There is very little evidence of a time trend in weight at age (Appendix A, Figure A1). The overall mean across all years, including landings, discards and surveys, was used for annual stock weights. For landings a simple mean across years for landings only was used. Similarly, for discards the mean was used for ages 0-3 but for 4 and older the stock weights were used (Table 1).

Natural mortality, M, shown Table 1 in was derived from the stock weights, w_s, using the Lorenzen(1996) formula where *a* is an index for age:

$$M_a = 3.69(w_{s,a})^{-0.305} \qquad (1)$$

Maturity at age is taken from the 6a stock values in ICES (2019) (Table 1). These differ marginally from those used by Adão (2025) where the proportions at ages 2 and 3 are 0.5 and 1.

It is important to note that the level of sampling both in the surveys and the discards is very low (Adão, 2025) with as few as two hauls per survey per year and around four observer trips per year. This inevitably leads to high sampling error and a large number of zero observations in the age compositions. Adequate modelling of zero values is important and discussed below.

Methods

Age structure stock assessment model (ASM)

An age structured stock assessment model was developed and configured for the Clyde data. The model is based on those of Cook (2019a, 2019b and Adão, 2025) with modifications to the error assumptions to accommodate zero observations and expanded to include multiple fleets. A gamma curve that allows dome shaped selectivity is assumed for the fishery, while survey selectivity is modelled with a logistic curve. Fishing mortality is assumed to be the product of a year effect and age dependent selectivity, where the year effect follows a random walk over time. Catches are described by the conventional Baranov equation and split into landings and discards with a time varying logistic retention function. Survey indices were assumed to be proportional to the number of fish in the sea.

Age compositions are modelled using a Dirichlet-multinomial model (Thorson *et al* 2017), which accommodates zero values, while abundance is sampled from lognormal distributions. A hurdle likelihood is used to allow the inclusion of zero catches that are not defined on a log scale. This is important since in recent years landings have been negligible or zero but convey a clear fishing mortality signal. A full model description is given in Appendix B.

Parameter estimation

Parameters were estimated from the data summarised in Figure 1 using the Bayesian statistical package “rstan” (Stan development team, 2016). Priors on the model parameters are given in Appendix B, Table B4. As far as possible, uniform priors were chosen with bounds set to avoid the estimates hitting limits. Log-uniform priors were used for initial population size to avoid negative values. The analysis was run using three MCMC chains for 60000 iterations, a burn in period of 30000 iterations and a thinning rate of 90. This gave 1000 samples that were saved for further analysis. Convergence was assessed using trace plots and the scale reduction statistic, Rhat.

Base run

A base model was run assuming two fleets- *Nephrops* trawl and “Other” gears. The latter comprises a number of gears including seine net, light trawl and pair trawl. However, light trawl dominates the catches and for simplicity this category is treated as one homogeneous fleet. As no age composition data on the discard component of Other gears are available, it is unlikely that the model can estimate separate selectivity for each fleet. Consequently, the fishery selectivity was assumed to be the same for both fleets and fixed over time. Similarly, while there are data on the total weight of fish discarded, the absence of associated age compositions makes it problematic to estimate separate retention curves (i.e. fish caught and retained as landings) for each fleet. It was assumed, therefore that the retention curve was the same for all fleets. The maximum age in the model was set to 5 as there are almost no fish above this age in the surveys and discards, and only a few fish up to age 7 in occasional years in the landings.

The Dirichlet-Multinomial model requires an estimate of the initial sample size, v. Generally, this will be much lower than the actual number of fish sampled. For this model run it was assumed that the sample size was 100 for the surveys and 500 for the landings and discards. The model estimates the effective sample size internally using this initial value (Thorson *et al*, 2017).

Sensitivity analysis

A number of sensitivity runs were done to investigate model assumptions and how different data streams affect the model estimates. These were:

i) The gamma fishery selectivity was replaced with a logistic curve (logistic_sel).
ii) The age compositions for the surveys were removed but the abundance indices retained (no_surv_agecomps).
iii) The first part of the quarter1 survey was omitted (both the age compositions and abundance) (no_Q1_surv).
iv) Natural mortality on older fish was increased to simulate increased migration out of the stock area (Table 1). (alt_m).

v) Natural mortality was estimated in the model by applying a multiplier, m, to the Lorenzen values $M_{a,y}$ in the equation:

$$Z_{a,y} = mM_{a,y} + \sum_g F_{a,y,g} \qquad (2)$$

With a prior on m taken from Hamel and Cope (2022):

$$m \sim lognormal(0,0.31) \qquad (3)$$

to replace equation T1.2 in Appendix B. (est_m)

vi) All the fishery data were omitted and the model fitted to the surveys only. The biomass was scaled to the quarter 1 part 1 survey (Survey_only).

vii) The total landed and discarded weights from 1985-2001 were omitted but the age compositions retained (no_lan_disc_wt).

viii) The oldest age was increased from 5 to 6 (max_age_6).

ix) The initial sample sizes were changed to 200 for the surveys, 1000 for landings and 100 for discards (smpl_size).

In addition to the above further sensitivity runs were undertaken to examine the potential effects of creel catches on the assessment. This is described in Appendix E.

Retrospective analysis

Model consistency was investigated with a standard set of retrospective runs removing up to 6 years of data from the base model run (Mohn, 1999). Summary statistics of SSB, F, recruitment and 50% retention age were used to compare runs. As the assessment in recent years depends on the two re-designed surveys that have only a short series of observations, removing more than 6 years of data leads to calibration problems as there is insufficient data to estimate the survey catchabilities.

MSY referenced points

Maximum sustainable yield (MSY) reference points were calculated from the base run. One thousand samples from the MCMC chains were saved when fitting the ASM model and used to estimate the reference points. For each sample a Beverton-Holt stock recruitment curve was fitted. Using the fitted relationship, biological parameters in Table 1 and selectivity derived from the model, the values of MSY, B_{MSY} and F_{MSY} were calculated. In addition, we calculated the value of F_{crash}, the fishing mortality that corresponds to the slope of the stock-recruitment curve at SSB=0. This gives the exploitation rate that would cause the stock to collapse. The 1000 estimates were used to construct a posterior distribution for each of the quantities. Similarly, we calculated the ratios F/F_{MSY}, B/B_{MSY} and F/F_{crash}.

At present all the catch in the fishery is assumed to be discarded, so MSY represents the total catch and is not confined landings. Here F_{MSY} can be thought of more usefully as an intrinsic biological characteristic of a stock since it is a function of the stock-recruitment relationship, natural mortality and growth .

Productivity

One of the concerns expressed about cod in the Clyde is the potential disturbance to spawning from fishing activity (Needle, 2022). A review by Zemeckis *et al* (2014) lists possible adverse effects on spawning cod by fishing operations. It has been suggested disruption of spawning behaviour may impair the fertilisation of eggs, or reduce larval viability, and hence harm future recruitment. While no quantitative studies have been reported, one possible line of inquiry is to estimate the productivity of the stock over time to see if changes have occurred. The log ratio,

$$P_y = log\left(N_{0,y}/SSB_y\right) \qquad (4)$$

where N_0 is recruitment and SSB is the spawning stock biomass, is an index of the survival of eggs from spawning to subsequent recruitment and can be seen as a measure of productivity, *P*. We calculated the ratio for each year from the results of the base model run to see if the index has changed through time. We also compared the ratio to the predicted productivity, $\bar{P}$ calculated from a fitted Beverton-Holt stock recruitment curve given by:

$$\bar{P} = \log(a) - \log\left(1 + bSSB\right) \qquad (5)$$

Where *a* and *b* are parameters of the Beverton-Holt curve.

We plotted the estimated productivity against fishing mortality to see if any negative relationship was apparent since fishing mortality might be considered as an indicator of disturbance.

Projection scenarios

Fishing mortality is one of the main variables that can be influenced through management intervention to change stock status. There are perhaps two principal ways to change fishing mortality; altering fishing activity and modifying the selection pattern. These equate to the year effect, *f* and the age effect *s*. We ran forward projections from the 2019 baseline under different assumptions of fishing activity, *f*, and fishing selectivity, *s*. For *f*, we applied a simple multiplier to the 2019 value for the *Nephrops* trawl fleet ranging from 0.4 to 1.2 in increments of 0.1, with zero applied to the “Other” fleets. We altered selectivity by changing the mode of the gamma selection curve in increments of 0.25 over the range -0.5 to 2.0. We ran a full set of combinations of *f* multipliers and mode increments. Each scenario was simulated on the complete set of 1000 MCMC samples.

A Beverton-Holt stock-recruitment function was fitted to each sample and used to generate recruitment in future years. Projections were then run for 30 years to give a steady state. As there is no directed fishery for cod, we only considered changes to SSB. Results are summarised as the median SSB estimated at steady state. We also calculated the probability that the SSB in five years ahead exceeded the SSB in the base year. This gives an indication of the magnitude of intervention required to facilitate stock recovery. We chose a five year time horizon since the current age composition of the stock is dominated by five age classes and projections beyond this period are comprised almost entirely of simulated year classes.

Surplus production model (SPM)

The age structured model assumes all the biological quantities such as growth, natural mortality and maturity are constant, and the dynamics are described simply by the decline in cohort numbers through time. In order to investigate alternative assumptions, we fitted a surplus production model based on the well-known Schaefer model which considers only changes in biomass and allows biological quantities to be density dependent. The model is framed as a delay-difference equation where the catch is disaggregated by fleet, landings and discards. A full description of the model is given in Appendix D. We assume the survey abundance indices are proportional to stock biomass. The catch is assumed to be a time varying fraction of the biomass at the start of the year. Landings are assumed to be a time varying proportion of the total catch, where the proportion follows a random walk on a logit scale.

Unlike ASM, the SPM provides direct estimates of MSY reference points and does not require the estimation of a stock-recruitment relationship. These differ somewhat from the age structured model in that the biomass in the surplus production model represents the partial exploited biomass (PEB) rather than the spawning stock biomass (SSB). For the ASM this can be defined as:

$$PEB_y = \sum_a N_{a,y} w_{s,a,y} s_a \qquad (6)$$

Where *N, w* and *s* are the number-at-age, weight-at-age and selectivity-at-age.

Furthermore, “fishing mortality” as represented in the SPM model is in effect a yield/biomass ratio not a true mortality rate. When comparing the results of the ASM with SPM we derived equivalent quantities for evaluation.

Results

Age structured model (ASM)

Figures showing the fit of the base model to the data are shown in Appendix C. The fit to catch data, both age compositions and catch biomass is good (Figure C6 to Figure C10). The fit to the age compositions for the surveys is not as close, especially for the quarter 4 survey (Figure C2 to Figure C5). The principal area of poor fit is to the quarter 1 part 1 survey abundance (Appendix C, Figure C1). There is clearly a trend in the residuals with the survey data indicating a shallower decline in abundance. In the remaining surveys, the fitted trend appears consistent with the data.

It is likely that the survey data are very noisy due to the small number of hauls carried out in the Clyde. For the surveys and discard age compositions, the estimated effective sample size ranged from 2.09 to 5.62 fish reflecting the very low number of trips or stations sampled. The effective sample size for the landings was 47.73, consistent with the much higher number of samples that are taken throughout the year. This means the model gives higher weight to the landings than other sources of data.

A summary of stock biomass, fishing mortality and recruitment is shown in Figure 2. SSB shows a sharp decline from the mid-1980s of around 1000 tonnes to only around 20 tonnes by 2019. Fishing mortality by fleet (Figure 2b) shows a rapid decline in “other” fleets from 2002 onwards. The reduction in this fleet is, however, compensated for by the increase in fishing mortality from the *Nephrops* trawl fleet. The total fishing mortality therefore remains high but with something of the decline in recent years. This is most clearly seen in Figure 8c (base run).

Recruitment shows a substantial decline from the early period to very low levels in the years 2000 onwards (Figure 2). Fishery selectivity reaches a peak at age 2 and declines rapidly thereafter (Figure 3). Survey catchability by age shows that young fish are less represented but are more or less fully selected by age 2 (Figure 4).

The 50% landings retention age for the commercial fishery is fairly constant at around age 1.25 up to 2000 after which it increases continuously to age 6 by the end of the time series (Figure 5). This reflects the absence of landings with all ages (sizes) of fish discarded in recent years.

Most of the sensitivity runs produced very similar results and are summarised in Figure 6. The model showed little sensitivity to assumptions about natural mortality, maximum age, initial sample size and the selection pattern of the fishery. There was also no evidence that the omission of creel catches made any material change to the perceived stock trends (Appendix E, Figure E3). There is weak evidence that natural mortality can be estimated since the posterior of the multiplier on M was left shifted compared to the prior (Figure 7), implying a lower value of natural mortality. However, there is substantial overlap in the distributions indicating any signal on the magnitude of natural mortality is weak.

When omitting landings and discarded weight, or using surveys only, there were substantial differences in the estimates (Figure 8). The revised survey design in 2011 is likely to contribute to the large change in estimated recruitment and SSB in the survey only run around this time as there are no catch data to help intercalibrate the surveys. However, the general picture of severe declines in SSB with high F is similar for all runs. The recent reduction in F is also apparent in all runs.

The results of the retrospective runs are shown in Figure 9. There is a high degree of consistency for SSB, and 50% retention age. In the case of mean F, while there is a significant revision for the 2016 terminal year, the same general pattern is retained regardless of the data removed. In the case of recruitment there are some very large revisions but since the terminal year estimate is entirely dependent on the number of 0-group fish sampled in the quarter 4 survey this is not surprising as there is only one observation of the recruiting class.

The stock-recruitment plot is shown in Figure 10a along with the replacement lines at current fishing mortality (F_{2019}) and F_{crash} , the fishing mortality where the expected equilibrium SSB is zero. Due to the large number of very small year classes in recent years this is plotted on a log scale to show these points more clearly. Current fishing mortality (F_{2019}) is very close to F_{crash}. MSY reference points and their credible intervals are shown in Table 2. The stock has been fished above F_{MSY} since 1985 with the SSB below B_{MSY} (Figure 10b) with a high degree of confidence. The SSB has been less than 10% of B_{MSY} since 2001(Figure 10b, dotted line). The fishing mortality has been close to or above F_{crash} for the entire period of the analysis. Figure 10c and d show the annual values of SSB and catch in relation to the expected equilibrium. There is some indication that the SSB is returning to a low equilibrium after a very weak upward trend (Figure 10c, red dots).

The time series of productivity shows a gradual increase up to 2005 and then some decline (Figure 11a). The annual estimates follow the predicted productivity from the fitted stock recruitment function closely. The most recent values have large credible intervals and are more uncertain but lie within the range seen historically. There is no apparent time trend in the residuals that might be correlated with an environmental trend (Figure 11b), nor is there any evidence of autocorrelation (Figure 11c). There is a positive relationship between productivity and F (Figure 11d) which does not support fishing activity as being detrimental to productivity.

A summary of the projection scenarios is shown in Figure 12. For the chances of an increase in SSB over five years to exceed 50%, an *f* reduction of at least 20% is required, or the mode of selectivity needs to increase by 0.5 years. The projected median steady state SSB at current fishing is in the range 100-150 tonnes, which is a modest increase on the 2019 estimate for 50 tonnes. Achieving SSB levels comparable to the late 1980s (around 500 tonnes) would require a reduction in *f* of about 50% or an increase in the selectivity mode by nearly two years. Clearly there is a trade-off between reductions in *f* and increases in the mode for any given choice of SSB.

Surplus production model (SPM)

The SPM produced similar results to ASM with declining biomass and a high level of exploitation (Figure 13a-c). The analysis also shows the stock below the MSY biomass threshold and above the MSY yield/biomass threshold with a high level of probability (Figure 13d). The partial exploited biomass (PEB) from SPM is indistinguishable from

ASM (Figure 14a). The credible intervals for the yield/biomass ratio from SPM are very large and completely enclose the estimates from ASM (Figure 14b). However, the median values do differ somewhat in recent years with SPM suggesting less of a decline.

Estimates of MSY reference points from SPM can be compared to ASM in Table 2. The estimates of MSY and PEB_{MSY} are very similar, though the median yield biomass ratio at MSY is somewhat higher from the SPM.

Discussion

Results from the assessment reflect those in Adão (2025) with a declining SSB and very high F. However, this earlier analysis was confined to survey data from 1985 onwards and discards data post 2002 which gave a low estimate of the initial biomass in 1985. Including the pre 2002 data on landings and discards described in this study revises the initial biomass upwards significantly since the data provide more information on scale. There is some conflicting signal between the early survey data and the early catch data that is seen most clearly in the poorer fit to the Q1 part 1 survey (Appendix C, Figure C1). Thus, while there is agreement on the general trend, the scale of the decline in SSB is less certain, as is the magnitude of the biomass at the start of the time series. However, most sensitivity runs where the assumptions about the survey or catch data were changed did not lead to major revisions to the estimated biomass and fishing mortality trajectories suggesting sensitivity to the data is fairly low when at least some survey and historical catch data are included. Retrospective analyses also suggest low sensitivity to the data as most runs lie within the credible intervals of the base run. Hence, the model appears well calibrated.

The ASM model base run makes strong assumptions about growth, natural mortality, fishery selectivity and the catch retention ogive. These can potentially bias any estimates of fishing mortality and spawning stock biomass. However, the SPM makes no explicit assumptions about these yet gives almost identical estimates of biomass and very similar estimates of fishing mortality. The assessment does not, therefore, appear to be sensitive to model structure.

Perhaps surprisingly, changing the selectivity pattern for the fishery made very little difference to the model results except for the scale of recruitment. Other changes, such as to natural mortality or initial sample size also made little difference. It seems therefore that the qualitative trends in SSB and F are robust and that the model is consistent.

It has been suggested that there is not enough data for the assessment of the Clyde stock (Needle, 2024). This would imply that any available data contain insufficient information to establish stock trends, or estimate reference points, and are dominated by noise. If so, one might expect different models to produce highly variable results, but this does not appear to be the case. When applying very different models (e.g. ASM vs SPM), that make fundamentally different assumptions about population dynamics, there is a high degree of consistency in the estimated biomass, exploitation and MSY reference points. It is highly likely that the data are adequate to assess stock status since both ASM and SPM show biomass below B_{MSY} and fishing mortality above F_{MSY} with a very high probability (Figure 10b and Figure 13c).

The trend in the productivity (Figure 10e) does not reveal any unexpected change. The rising productivity from the mid-1980s is consistent with most conventional stock recruitment curves including the Beverton-Holt curve shown in Figure 10a. Here density dependent effects dominate when the SSB is high reducing productivity. However, the recent indices do indicate a decline. It is not possible to attribute this change to any specific cause and there is a multitude of human, biological and environmental factors that may be involved. In any event, the current productivity is well within the range experienced historically and is higher than the productivity in the mid1980s when the stock biomass was 40 times larger. Furthermore, productivity peaked when the SSB reached its lowest values between 2003-2007. This does not suggest the stock has declined due to external factors reducing productivity but does imply fishing mortality is the principal cause.

Directed fishing for whitefish has ceased in the Clyde and this is apparent from the decline in fishing mortality for all fleets included in the analysis apart from the directed *Nephrops* trawl fleet. While *Nephrops* trawl does not target whitefish, there is nevertheless bycatch that includes cod (McIntyre *et al* 2012). Recent cod catches by this fleet are in the region of 50t which is small in comparison to the total catches in the mid-1980s that were as high as 2000t. However, this bycatch is taken from a small stock and it generates a very high fishing mortality that would be expected to remove around 80% of the biomass each year (Figure 13c). Such high pressure is unlikely to be sustainable. It is possible that the estimates of fishing mortality are biased upward due to fish emigrating out of the Clyde as they get older. The sensitivity run that inflated natural mortality by a modest amount on older fish to simulate emigration made very little difference to the estimates. This would suggest that emigration would have to be very large to account for high bias in F. The results of tagging studies do not support sizable emigration from the Clyde (Wright et al, 2006). Estimating natural mortality within the model gave no indication that the Lorenzen based values were too low.

Currently there is an area closed to fishing when Clyde cod spawn. Whatever the conservation benefits of the closure, it has not been sufficient to reduce fishing mortality to sustainable levels. There have been recent additional restrictions on static gears in the hope that the productivity of the stock will improve by reducing disturbance to cod spawning behaviour and increase recruitment. The potential benefits of such restrictions are hard to quantify and need to be weighed against any detriment to the affected fisheries. The most recent recruitment (Figure 10a, red dots) lies below the replacement line at the 2019 fishing mortality, which if maintained, would lead to further stock decline. For the decline to be halted, recruitment (productivity) at the 2019 SSB would have to be enhanced to 3.3 times its current level. This would still not lead to stock recovery but only prevent further decline. It is a matter of conjecture whether protecting spawning behaviour could achieve such a large improvement in recruitment.

Recent recruitment values lie above the F_{MSY} replacement line and stock recovery might be expected regardless of any improvement in productivity when fishing at F_{MSY}. Achieving F_{MSY} would require a reduction in cod bycatch of about 75%, but even a modest reduction of 25% would be expected to reach an SSB in excess of 400t over time (F=1.3 in Figure 10c) compared to the 2019 value of 32t.

The benefits of reducing disturbance to spawning behaviour to enhance recruitment are largely a matter of speculation in the absence of any quantitative analysis. There are multiple possible causes of disturbance that include noise due to shipping, predation by seals and other predators, and seasonal storms. Fishing activity is just one source which may only make a minor contribution to disturbance. The SSB effectively collapsed around the year 2000 and current fishing mortality is too high to sustain a viable spawning stock since F is close to F_{crash}. It is associated with the bycatch in the *Nephrops* trawl fishery which needs to be the primary focus for management if stock recovery is the objective. Bycatch can be reduced through lower fishing activity but this may be unattractive since cod are not the target species for the principal fleet (*Nephrops* trawl) involved. Simulations indicate that improving selectivity so that a higher proportion of younger fish escape capture may be beneficial and might be achieved through changes to gear design.

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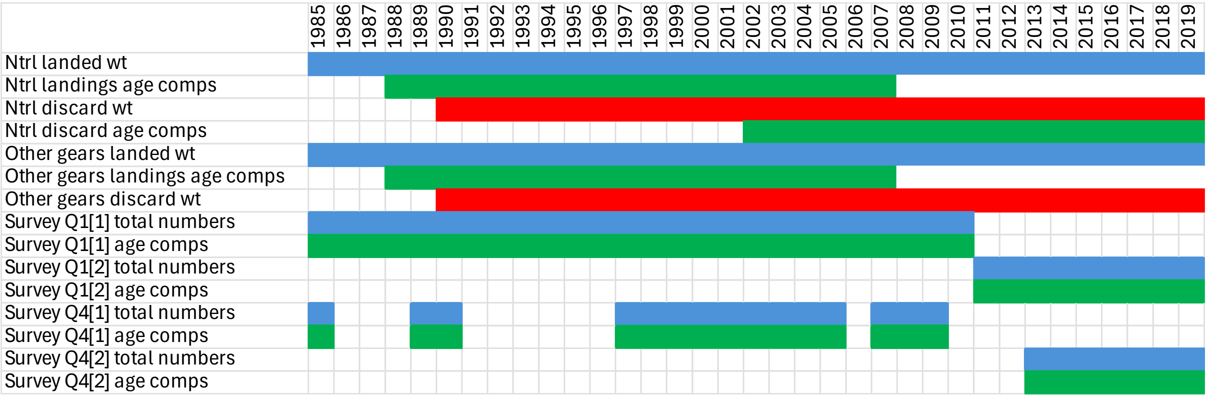
Table 1. Biological constants used in the model.

Age	Landing weights (kg), w_l	Discards weights (kg), w_d	Stock weights (kg),w_s	Proportion mature	Natural mortality, M	Natural mortality, sensitivity run
0	-	0.058	0.063	0	1.04	1.04
1	0.598	0.175	0.297	0	0.65	0.65
2	0.907	0.467	0.945	0.52	0.46	0.56
3	2.410	1.544	2.301	0.86	0.35	0.50
4	4.010	3.878	3.878	1.00	0.30	0.50
5	5.769	5.619	5.619	1.00	0.27	0.52
6	8.009	7.840	7.840	1.00	0.24	0.52

Table 2. Estimates of MSY reference points for the age structured model (ASM) and the surplus production model (SPM). Biomass values are given in tonnes.

	ASM			SPM		
	Lower 2.5%	Median	Upper 97.5%	Lower 2.5%	Median	Upper 97.5%
F_{MSY}	0.48	0.56	0.67		-	
B_{MSY}	1807	2431	3473		-	
MSY	682	892	1247	309	942	1466
PEB_{MSY}	1614	2316	3555	1545	2171	2436
Y/PB_{MSY}	0.34	0.38	0.44	0.16	0.46	0.73



	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
Ntrl landed wt	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦
Ntrl landings age comps				🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩												
Ntrl discard wt						🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥
Ntrl discard age comps																		🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
Other gears landed wt	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦
Other gears landings age comps				🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩												
Other gears discard wt						🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥
Survey Q1[1] total numbers	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦									
Survey Q1[1] age comps	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩									
Survey Q1[2] total numbers																											🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦
Survey Q1[2] age comps																											🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
Survey Q4[1] total numbers	🟦				🟦	🟦							🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦		🟦	🟦	🟦										
Survey Q4[1] age comps	🟩				🟩	🟩							🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩		🟩	🟩	🟩										
Survey Q4[2] total numbers																													🟦	🟦	🟦	🟦	🟦	🟦	🟦
Survey Q4[2] age comps																													🟩	🟩	🟩	🟩	🟩	🟩	🟩

Figure 1. Summary of data included in the ASM assessment. Ntrl=Nephrops trawl.

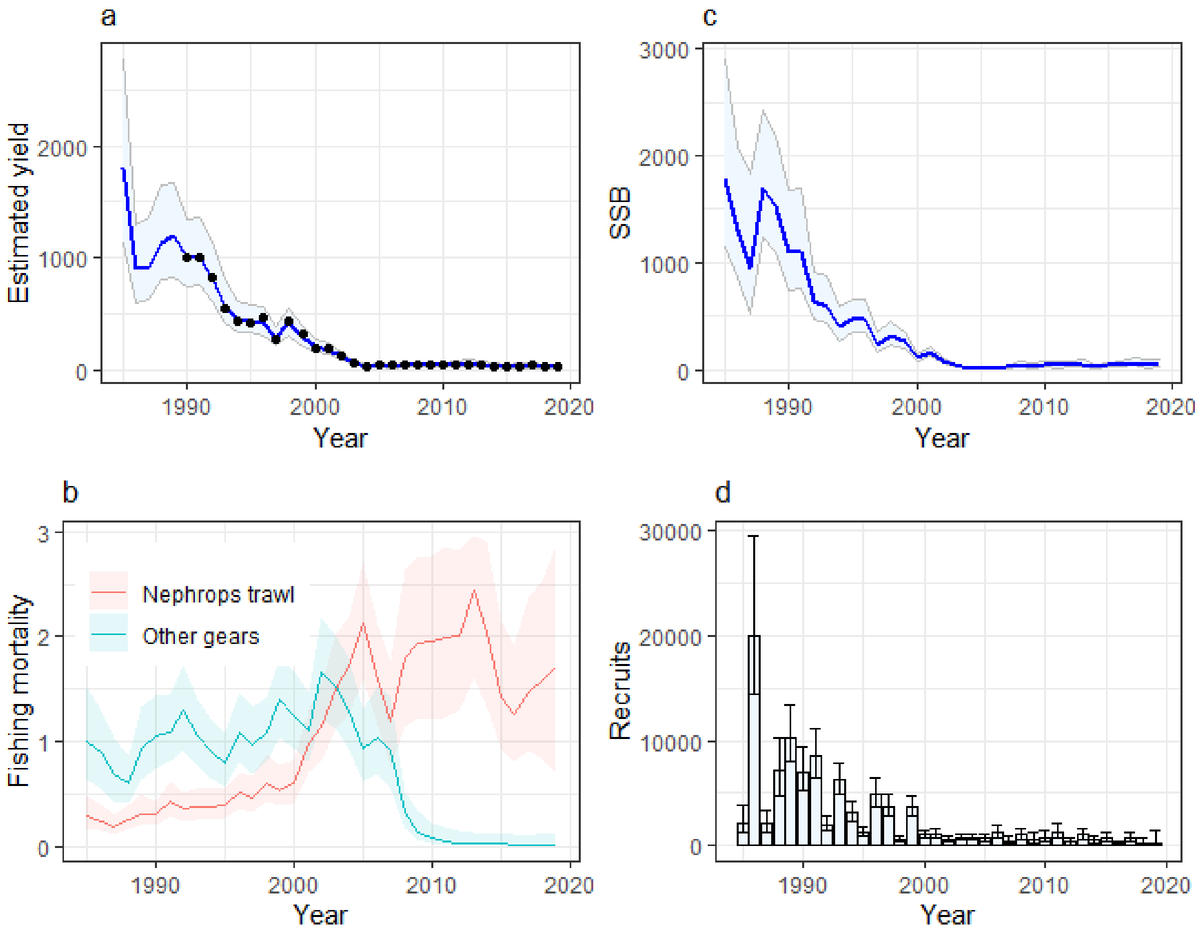


Figure 2. Base model stock summary. Solid lines (a-c) show median values and shaded areas the 95% credible interval. Dots in (a) show the total catch data. (d) Recruitment in numbers where bars indicate median values with 95% credible intervals. SSB and yield are shown in tonnes.

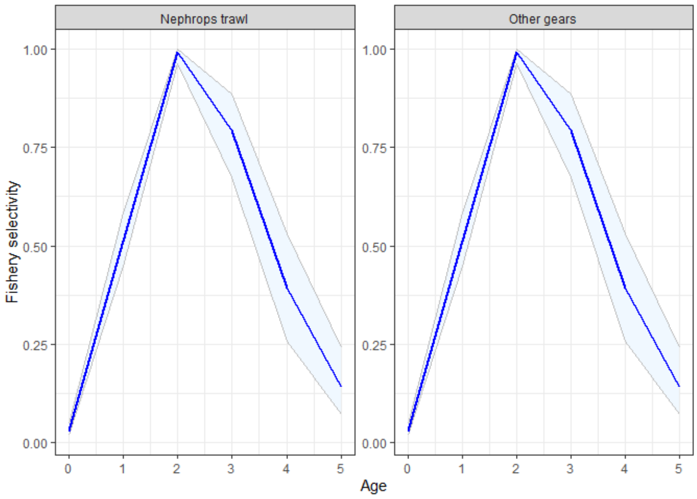


Figure 3. Base model. Estimated fleet selectivity. Selectivity is assumed to be the same for both fleets and described by a gamma curve.

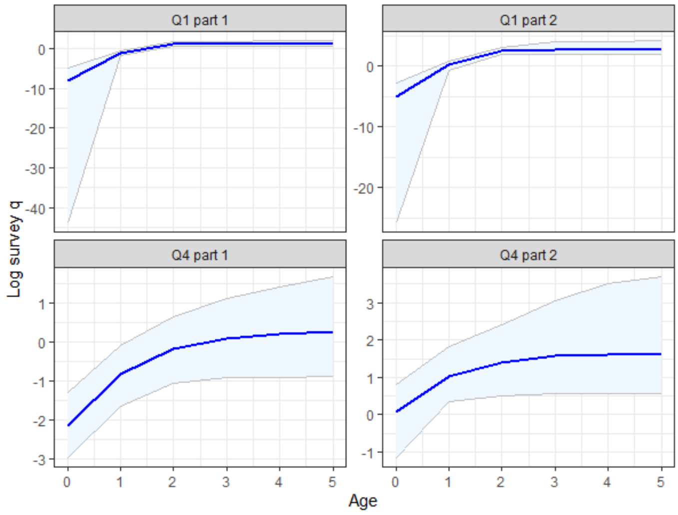


Figure 4. Base model. Estimated catchability at age for each survey. Selectivity is assumed logistic.

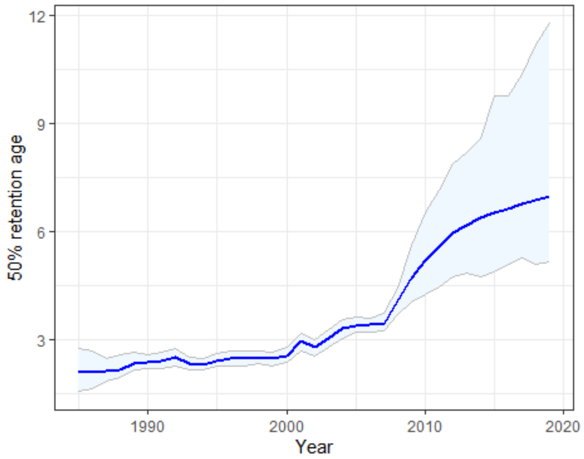


Figure 5. Base model. Estimated 50% retention age for landed fish.

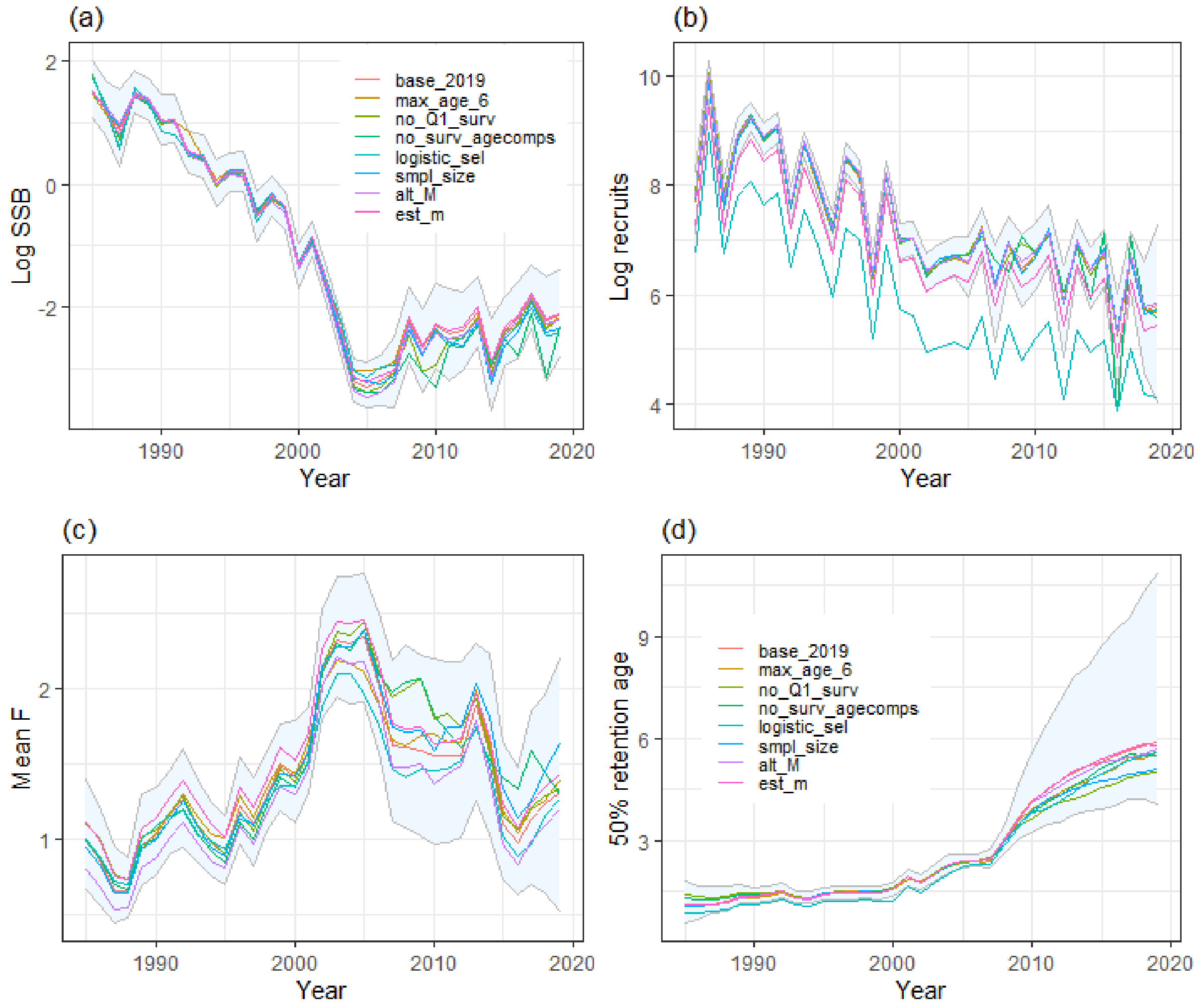


Figure 6. Sensitivity run summary for models that that gave similar results to the base model. Shaded area is the 95% credible interval for the base run. All the sensitivity results fall within the base run credible intervals with only one exception (logistic selectivity in the recruitment estimates (b)). Log scales are used for SSB and recruitment to aid clarity

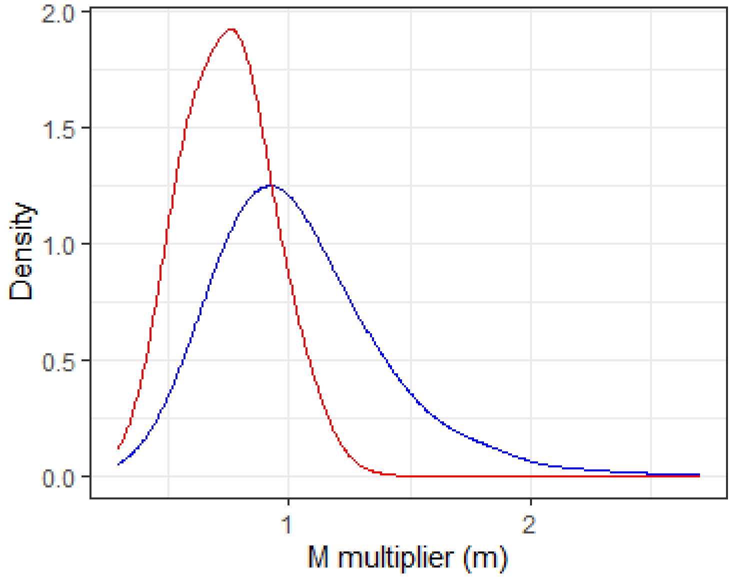


Figure 7. Prior (blue) and posterior (red) distributions for the multiplier, m, on natural mortality.

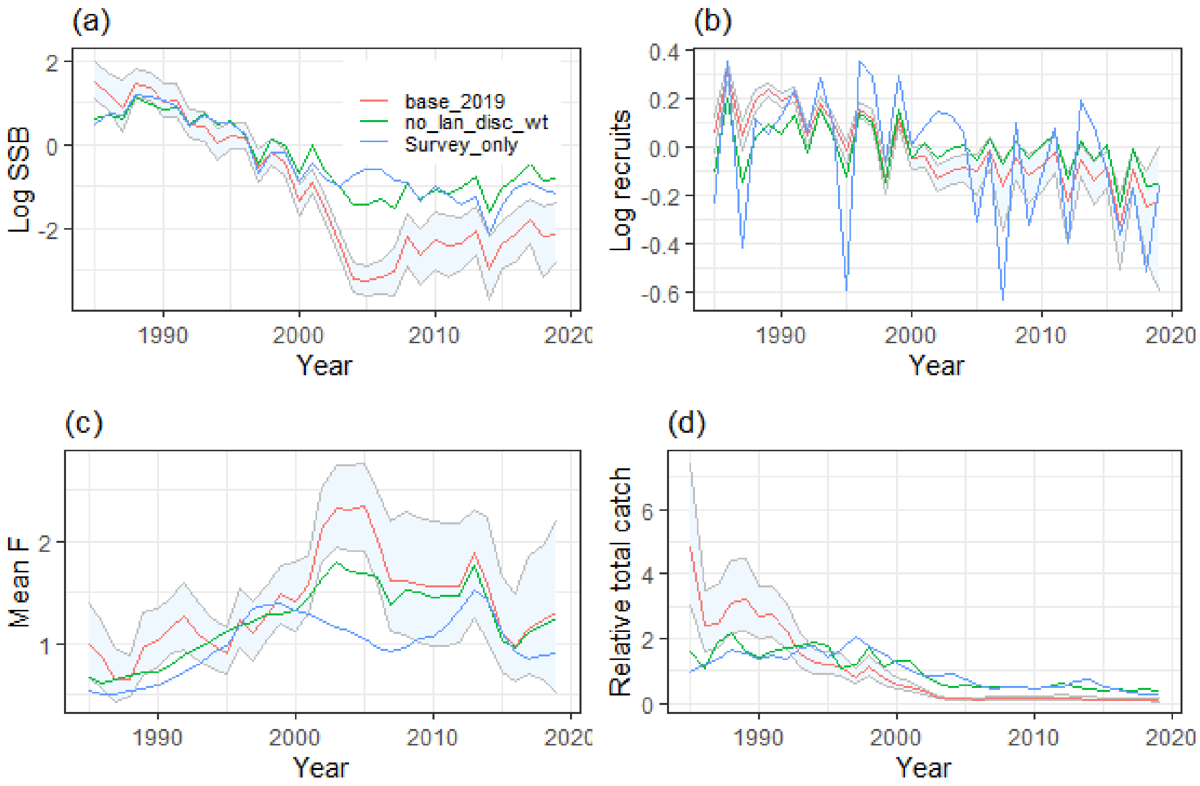


Figure 8. Comparison of base model to surveys only model or omitting the landings and discard weight pre 2002. Data for SSB and recruits are scaled to the time series mean for comparison. Shaded area is the 95% credible interval for the base run. (a), (b) and (d) show the time series scaled to the series mean.

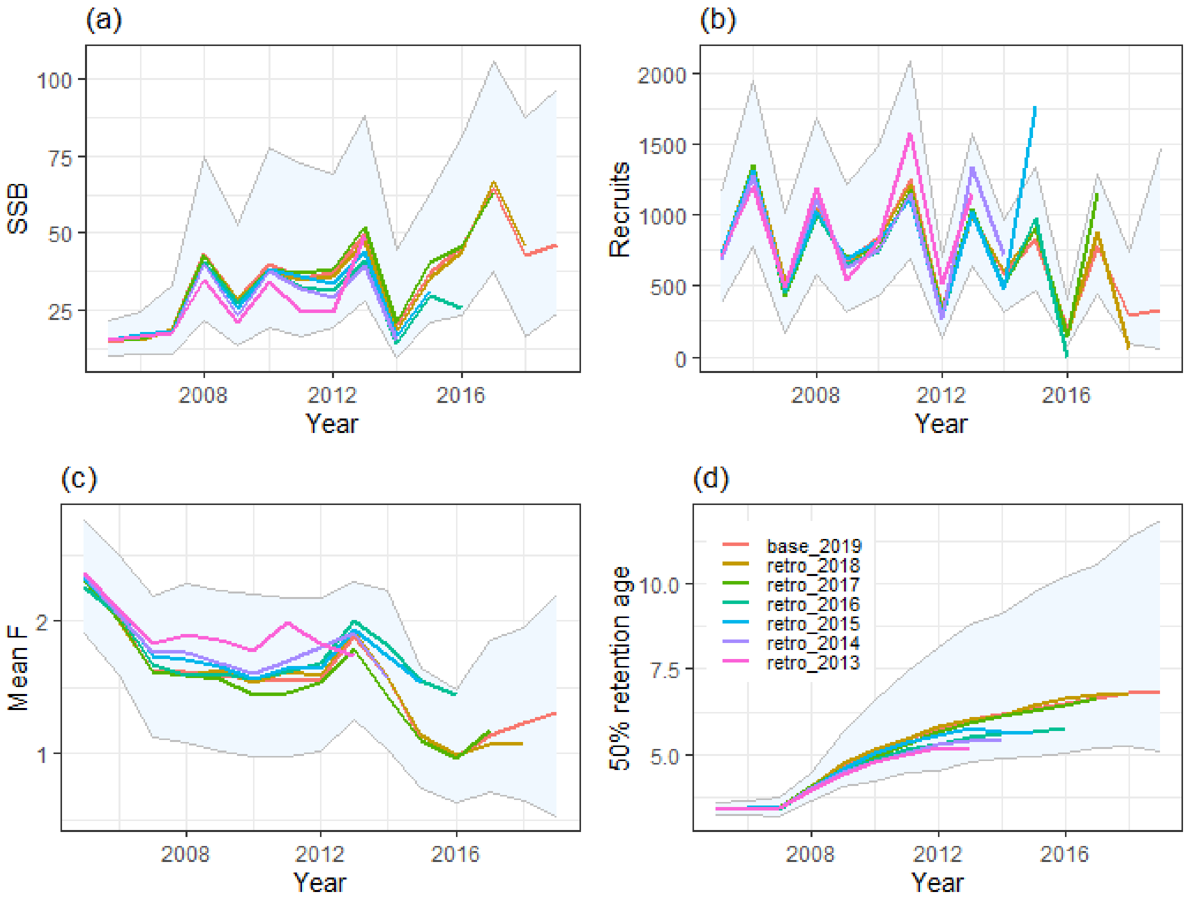


Figure 9. Retrospective runs from the base model. Shaded area shows the 95% credible interval for the base run. For these models, all historical estimates lie within the base run credible intervals.

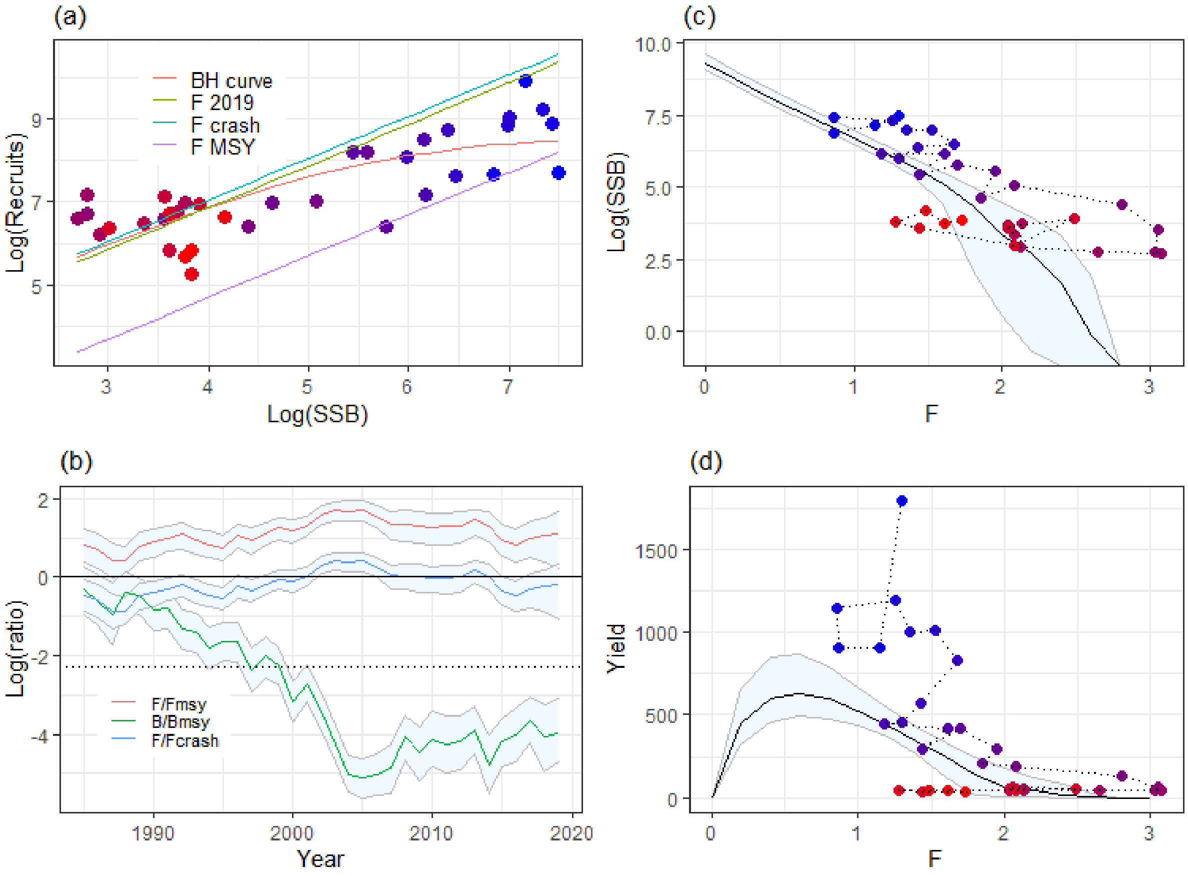


Figure 10. Results of MSY analysis. (a) shows the stock recruitment plot with fitted Beverton-Holt curve (red)(R squared=0.68). Replacement lines corresponding to $_{FMSY}$ (purple), F_{2019} (green) and F_{crash} (blue) are also shown. The colour of the dots grades from blue in the early years to red for the most recent. (b) shows the change in SSB and F relative to MSY (red and green lines). The solid black line corresponds to the ratio at MSY. The dotted line shows the biomass ratio when the SSB is 10% of B_{MSY}. The blue line shows F relative to F_{crash}. (c) shows the equilibrium SSB for any value of F (black line). Points show the estimated SSB each year relative to the equilibrium. The time sequence is indicated by the colour of the dots (blue from 1985 to red in 2019). (d) shows the equilibrium yield expected for any value of F (black line). Points show the estimated catch each year relative to the equilibrium. The time sequence is indicated by the colour of the dots as in (c). Log scales have been used for a, b and c to avoid compressing the low SSB values and to aid clarity.

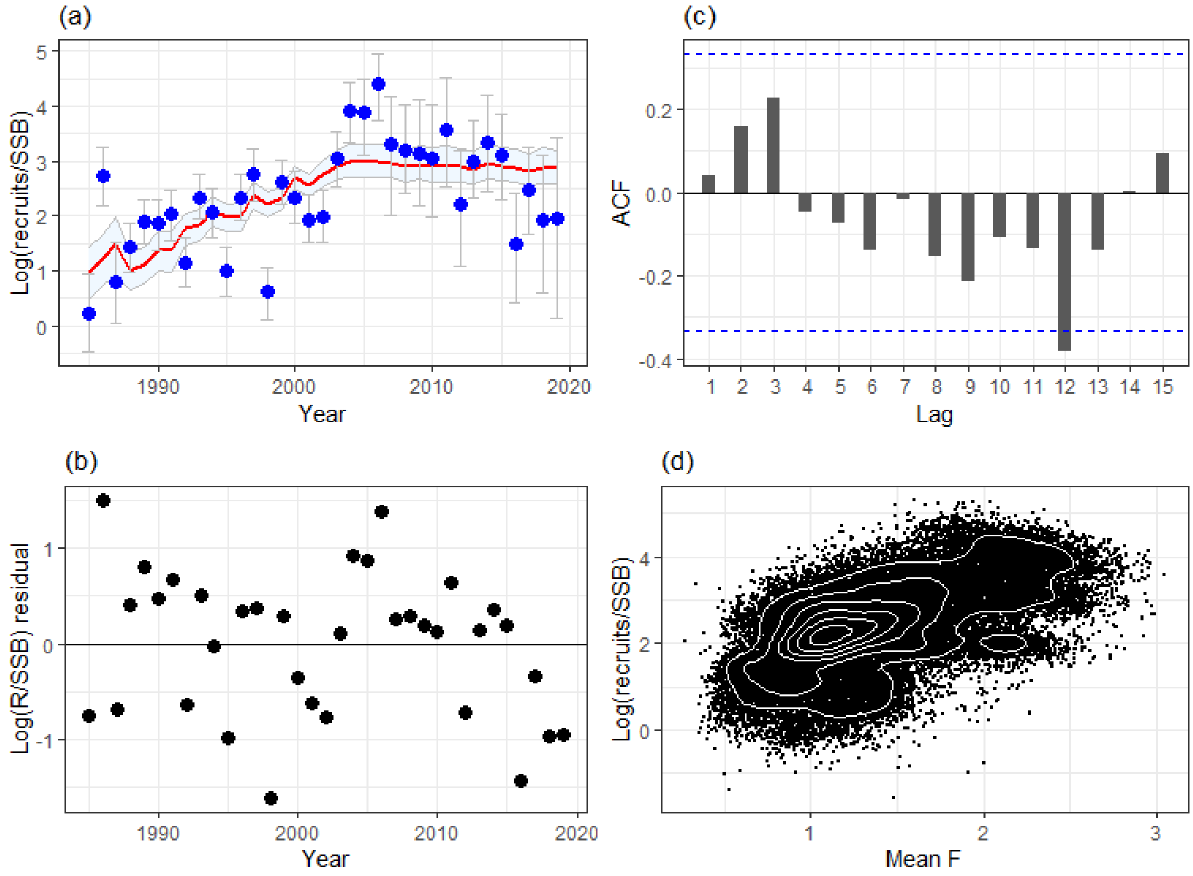


Figure 11. Productivity as measured by log(recruits/SSB). (a) shows the productivity of the stock as measured by the survival between spawning and subsequent recruitment. Dots show the median value and error bars the 95% credible interval. The red line is the expected median productivity based on the fitted stock-recruitment relationship with 95% credible intervals shown as a shaded area. (b) shows the residuals between medians of the predicted and estimated productivity plotted as a time series. (c) is the autocorrelation function (ACF) for the residuals in (b) where the dotted lines show the 95% confidence interval. (d) shows the productivity for each MCMC sample plotted against fishing mortality as an index of fishing activity. Contours show the density of the points.

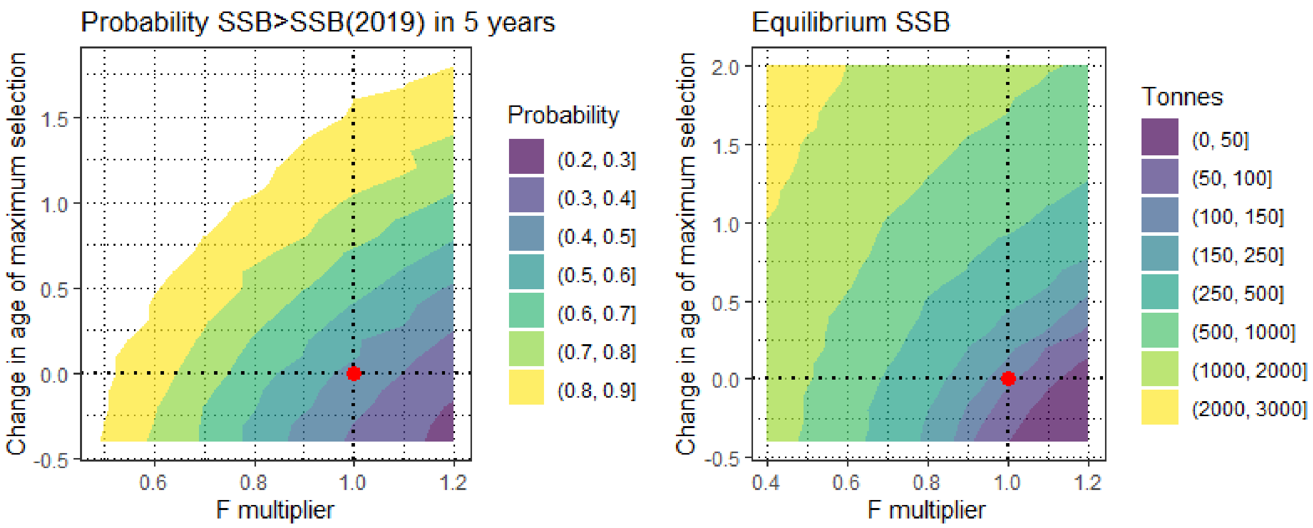


Figure 12. Summary of the projection scenarios. Y axis shows the increment in the age of maximum selection. X axis shows the multiplier applied to the 2019 fishing mortality. The red dot indicates the current (2019) values for the multiplier and change in age of maximum selection. Left panel shows the probability that the SSB increases after five years compared to the 2019 value. Right panel shows the median SSB after 30 years.

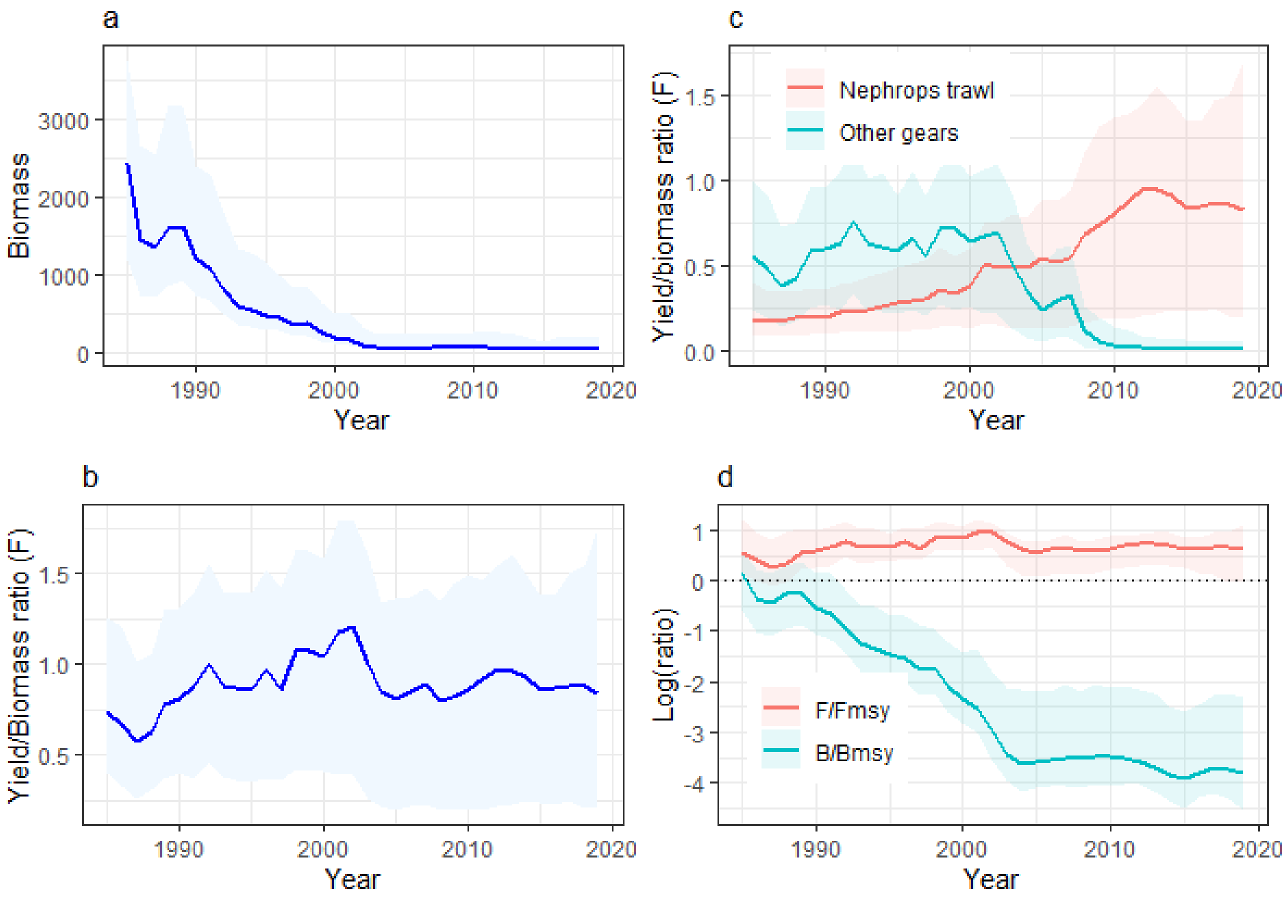


Figure 13. Summary of the Clyde stock assessment from the SPM model. (a) Partial exploited biomass (tonnes), (b) Total yield/biomass ratio, F, (c) Yield/biomass ratio by fleet and (d) Stock changes relative to MSY. Dotted line indicates a ratio of 1:1 on a log scale which is the MSY level.

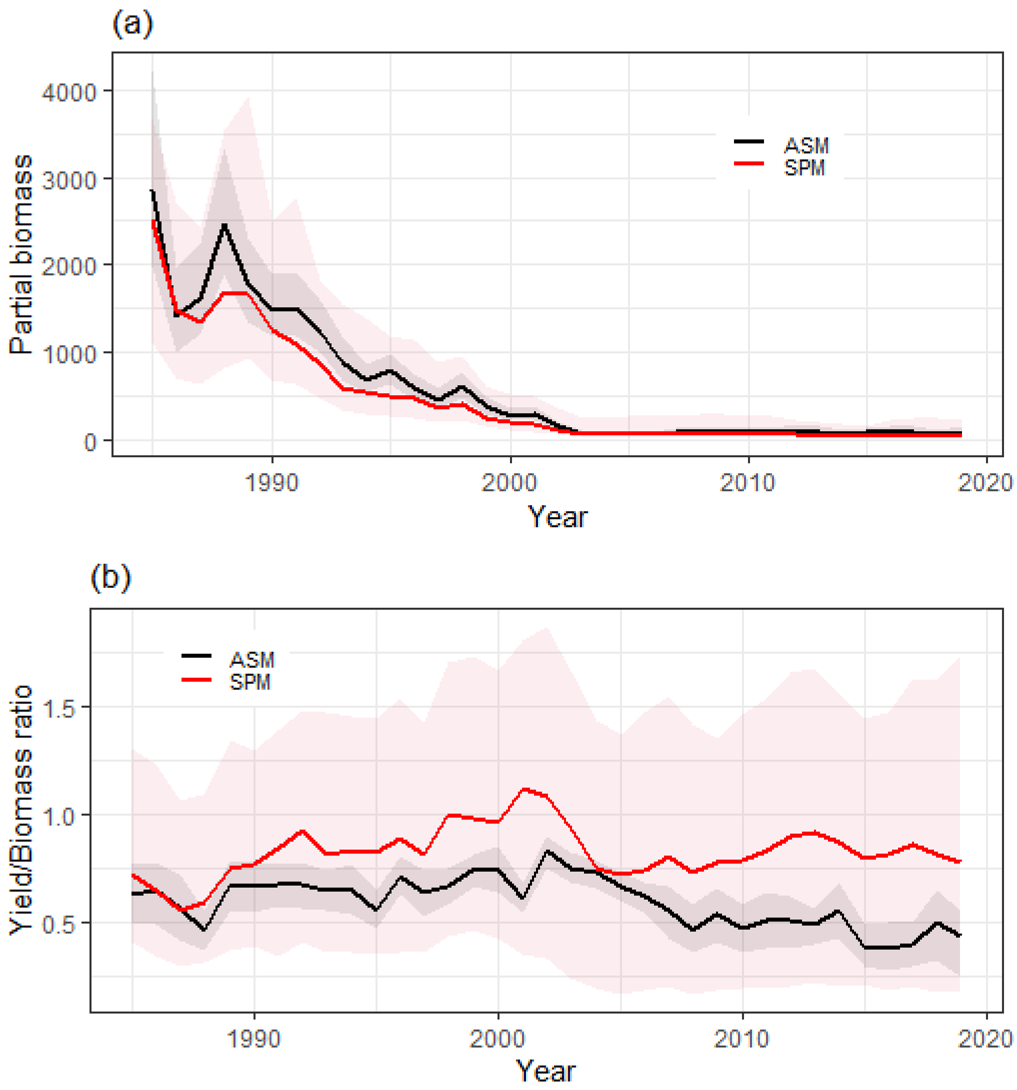


Figure 14. Results from the SPM model compared to ASM. Solid lines how the median values. Shaded areas are the 95% credible intervals. (a) Partial exploited biomass, PEB in tonnes. (b) Yield biomass ratio.

Appendix A. Data

Data used in the age structured model

*Table A 1. Quarter 1 survey age compositions as proportions at age. The total is the abundance expressed as numbers per hour*100. Data from 2011 onwards are treated as a separate survey due to a change of survey design.*

	Age								
Year	0	1	2	3	4	5	6	7	Total number
1985	0.00	0.26	0.63	0.11	0.00	0.00	0.00	0.00	950
1986	0.00	0.00	0.38	0.50	0.13	0.00	0.00	0.00	400
1987	0.00	0.94	0.02	0.03	0.01	0.00	0.00	0.00	11250
1988	0.00	0.00	0.48	0.44	0.04	0.04	0.00	0.00	1250
1989	0.00	0.13	0.05	0.81	0.01	0.00	0.00	0.00	2633
1990	0.00	0.11	0.47	0.00	0.42	0.00	0.00	0.00	950
1991	0.00	0.59	0.18	0.18	0.00	0.05	0.00	0.00	1148
1992	0.00	0.52	0.26	0.17	0.00	0.00	0.00	0.04	1150
1993	0.00	0.07	0.73	0.18	0.02	0.00	0.00	0.00	2250
1994	0.00	0.48	0.19	0.26	0.06	0.00	0.00	0.00	1550
1995	0.00	0.26	0.68	0.05	0.00	0.00	0.00	0.00	950
1996	0.00	0.05	0.25	0.61	0.07	0.00	0.02	0.00	2200
1997	0.00	0.91	0.00	0.09	0.00	0.00	0.00	0.00	1150
1998	0.00	0.55	0.45	0.00	0.00	0.00	0.00	0.00	550
1999	0.00	0.07	0.57	0.36	0.00	0.00	0.00	0.00	700
2000	0.00	0.71	0.05	0.24	0.00	0.00	0.00	0.00	2100
2001	0.00	0.27	0.64	0.09	0.00	0.00	0.00	0.00	1100
2002	0.00	0.50	0.38	0.13	0.00	0.00	0.00	0.00	533
2003	0.00	0.33	0.50	0.17	0.00	0.00	0.00	0.00	600
2004	0.00	0.40	0.30	0.30	0.00	0.00	0.00	0.00	2000
2005	0.00	0.33	0.33	0.33	0.00	0.00	0.00	0.00	300
2006	0.00	0.00	0.33	0.67	0.00	0.00	0.00	0.00	300
2007	0.00	0.38	0.38	0.25	0.00	0.00	0.00	0.00	533
2008	NA	NA	NA	NA	NA	NA	NA	NA	NA
2009	0.00	0.22	0.45	0.33	0.00	0.00	0.00	0.00	600
2010	0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00	200
2011	0.00	0.14	0.43	0.43	0.00	0.00	0.00	0.00	467
2012	0.00	0.38	0.58	0.04	0.00	0.00	0.00	0.00	1778
2013	0.00	0.15	0.74	0.11	0.00	0.00	0.00	0.00	1800
2014	0.00	0.83	0.17	0.00	0.00	0.00	0.00	0.00	800
2015	0.00	0.33	0.67	0.00	0.00	0.00	0.00	0.00	450
2016	0.00	0.38	0.46	0.15	0.00	0.00	0.00	0.00	975
2017	0.00	0.13	0.25	0.38	0.25	0.00	0.00	0.00	800
2018	0.00	0.10	0.20	0.50	0.20	0.00	0.00	0.00	667
2019	0.00	0.22	0.67	0.11	0.00	0.00	0.00	0.00	635

*Table A 2 Quarter 4 survey age compositions as proportions at age. The total is the abundance expressed as numbers per hour*100. Data from 2011 onwards are treated as a separate survey due to a change of survey design.*

Year	0	1	2	3	4	5	6	7	Total
1985	0	0	0	0	0	0	0	0	0
1986	NA	NA	NA	NA	NA	NA	NA	NA	NA
1987	NA	NA	NA	NA	NA	NA	NA	NA	NA
1988	NA	NA	NA	NA	NA	NA	NA	NA	NA
1989	0.00	0.78	0.10	0.12	0.00	0.00	0.00	0.00	425
1990	0.00	0.93	0.07	0.00	0.00	0.00	0.00	0.00	941
1991	NA	NA	NA	NA	NA	NA	NA	NA	NA
1992	NA	NA	NA	NA	NA	NA	NA	NA	NA
1993	NA	NA	NA	NA	NA	NA	NA	NA	NA
1994	NA	NA	NA	NA	NA	NA	NA	NA	NA
1995	NA	NA	NA	NA	NA	NA	NA	NA	NA
1996	NA	NA	NA	NA	NA	NA	NA	NA	NA
1997	0	0	0	0	0	0	0	0	0
1998	0.14	0.71	0.14	0.00	0.00	0.00	0.00	0.00	700
1999	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	100
2000	0.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00	100
2001	0	0	0	0	0	0	0	0	0
2002	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	100
2003	0	0	0	0	0	0	0	0	0
2004	0	0	0	0	0	0	0	0	0
2005	0	0	0	0	0	0	0	0	0
2006	NA	NA	NA	NA	NA	NA	NA	NA	NA
2007	0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00	67
2008	0.67	0.00	0.33	0.00	0.00	0.00	0.00	0.00	200
2009	0.33	0.67	0.00	0.00	0.00	0.00	0.00	0.00	200
2010	NA	NA	NA	NA	NA	NA	NA	NA	NA
2011	NA	NA	NA	NA	NA	NA	NA	NA	NA
2012	0.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00	333
2013	NA	NA	NA	NA	NA	NA	NA	NA	NA
2014	0.14	0.86	0.00	0.00	0.00	0.00	0.00	0.00	553
2015	0.94	0.06	0.00	0.00	0.00	0.00	0.00	0.00	1133
2016	0.00	0.67	0.33	0.00	0.00	0.00	0.00	0.00	198
2017	0.91	0.09	0.00	0.00	0.00	0.00	0.00	0.00	1048
2018	0.00	0.50	0.25	0.00	0.25	0.00	0.00	0.00	296
2019	0.50	0.50	0.00	0.00	0.00	0.00	0.00	0.00	320

Table A 3 Nephrops trawl landings proportions at age.

	Age							
Year	0	1	2	3	4	5	6	7
1987	0.00	0.82	0.11	0.04	0.02	0.00	0.00	0.00
1988	0.00	0.03	0.96	0.01	0.00	0.00	0.00	0.00
1989	0.00	0.28	0.18	0.53	0.00	0.00	0.01	0.00
1990	0.00	0.45	0.49	0.02	0.04	0.00	0.00	0.00
1991	0.00	0.22	0.72	0.04	0.01	0.00	0.00	0.00
1992	0.00	0.34	0.53	0.12	0.01	0.00	0.00	0.00
1993	0.00	0.08	0.86	0.05	0.01	0.00	0.00	0.00
1994	0.00	0.55	0.25	0.18	0.01	0.00	0.00	0.00
1995	0.00	0.06	0.91	0.02	0.01	0.00	0.00	0.00
1996	0.00	0.04	0.73	0.22	0.00	0.00	0.00	0.00
1997	0.00	0.44	0.38	0.14	0.04	0.00	0.00	0.00
1998	0.00	0.14	0.84	0.02	0.00	0.00	0.00	0.00
1999	0.00	0.02	0.92	0.06	0.00	0.00	0.00	0.00
2000	0.00	0.72	0.15	0.12	0.01	0.00	0.00	0.00
2001	0.00	0.03	0.96	0.01	0.00	0.00	0.00	0.00
2002	0.00	0.17	0.54	0.29	0.00	0.00	0.00	0.00
2003	0.00	0.13	0.81	0.04	0.02	0.00	0.00	0.00
2004	0.00	0.36	0.51	0.13	0.01	0.00	0.00	0.00
2005	0.00	0.04	0.88	0.08	0.00	0.00	0.00	0.00
2006	0.00	0.03	0.84	0.12	0.01	0.00	0.00	0.00
2007	0.00	0.02	0.76	0.20	0.01	0.01	0.00	0.00

Table A 4 Other gears landings proportions at age.

	Age							
Year	0	1	2	3	4	5	6	7
1987	0.00	0.83	0.13	0.02	0.02	0.00	0.00	0.00
1988	0.00	0.12	0.86	0.02	0.00	0.00	0.00	0.00
1989	0.00	0.18	0.22	0.59	0.01	0.00	0.00	0.00
1990	0.00	0.27	0.64	0.03	0.06	0.00	0.00	0.00
1991	0.00	0.20	0.69	0.10	0.00	0.01	0.00	0.00
1992	0.00	0.10	0.69	0.20	0.01	0.00	0.00	0.00
1993	0.00	0.10	0.84	0.05	0.01	0.00	0.00	0.00
1994	0.00	0.42	0.43	0.13	0.01	0.01	0.00	0.00
1995	0.00	0.08	0.88	0.02	0.01	0.01	0.00	0.00
1996	0.00	0.08	0.67	0.22	0.02	0.01	0.00	0.00
1997	0.00	0.32	0.44	0.19	0.05	0.00	0.00	0.00
1998	0.00	0.13	0.85	0.02	0.00	0.00	0.00	0.00
1999	0.00	0.11	0.58	0.28	0.03	0.00	0.00	0.00
2000	0.00	0.43	0.28	0.26	0.02	0.00	0.00	0.00
2001	0.00	0.21	0.79	0.00	0.00	0.00	0.00	0.00
2002	0.00	0.30	0.47	0.23	0.00	0.00	0.00	0.00
2003	0.00	0.30	0.65	0.03	0.02	0.00	0.00	0.00
2004	0.00	0.44	0.43	0.13	0.01	0.00	0.00	0.00
2005	0.00	0.26	0.64	0.10	0.00	0.00	0.00	0.00

2006	0.00	0.00	0.88	0.11	0.01	0.00	0.00	0.00
2007	0.00	0.06	0.71	0.22	0.01	0.00	0.00	0.00

Table A 5 Nephrops trawl discard proportions at age.

				Age				
Year	0	1	2	3	4	5	6	7
2002	0.04	0.96	0.00	0.00	0.00	0.00	0.00	0.00
2003	0.12	0.75	0.04	0.08	0.00	0.00	0.00	0.00
2004	0.09	0.86	0.05	0.00	0.00	0.00	0.00	0.00
2005	0.48	0.47	0.05	0.00	0.00	0.00	0.00	0.00
2006	0.10	0.87	0.01	0.01	0.00	0.00	0.00	0.00
2007	0.25	0.75	0.00	0.00	0.00	0.00	0.00	0.00
2008	0.00	0.82	0.18	0.00	0.00	0.00	0.00	0.00
2009	0.25	0.75	0.00	0.00	0.00	0.00	0.00	0.00
2010	0.51	0.49	0.00	0.00	0.00	0.00	0.00	0.00
2011	0.68	0.27	0.04	0.01	0.00	0.00	0.00	0.00
2012	0.00	0.96	0.04	0.00	0.00	0.00	0.00	0.00
2013	0.25	0.70	0.04	0.00	0.00	0.00	0.00	0.00
2014	0.03	0.96	0.02	0.00	0.00	0.00	0.00	0.00
2015	0.33	0.54	0.13	0.00	0.00	0.00	0.00	0.00
2016	0.00	0.99	0.01	0.00	0.00	0.00	0.00	0.00
2017	0.20	0.14	0.66	0.00	0.00	0.00	0.00	0.00
2018	0.04	0.96	0.00	0.00	0.00	0.00	0.00	0.00
2019	0.01	0.42	0.57	0.00	0.00	0.00	0.00	0.00

Table A 6 Catch biomass (tonnes) by fleet and category.

	Nephrops trawl		Other gears	
Year	Landings	Discards	Landings	Discards
1985	380.55	NA	1382.35	NA
1986	187.22	NA	712.77	NA
1987	109.85	NA	539.91	NA
1988	350.17	NA	638.60	NA
1989	303.53	NA	974.05	NA
1990	136.44	51.03	592.16	221.46
1991	239.87	69.18	544.67	157.08
1992	109.93	52.12	447.90	212.37
1993	140.79	14.80	365.61	38.43
1994	95.14	33.70	233.57	82.73
1995	125.05	20.18	245.69	39.65
1996	129.66	18.25	284.95	40.10
1997	63.23	24.96	134.38	53.04
1998	138.33	38.29	207.68	57.49
1999	67.23	7.83	218.72	25.48
2000	41.55	19.35	98.56	45.90
2001	46.02	62.52	40.21	54.64
2002	38.05	12.42	63.94	20.87
2003	13.41	18.42	13.50	18.54
2004	4.99	18.02	4.03	14.56
2005	3.51	29.98	1.17	10.01
2006	1.65	28.29	1.19	20.27
2007	1.83	24.55	2.36	31.58
2008	1.82	42.32	0.26	5.93
2009	0.00	47.90	0.00	0.00
2010	0.00	51.27	0.00	0.00
2011	0.00	55.74	0.00	0.00
2012	0.00	56.10	0.00	0.00
2013	0.00	51.00	0.00	0.00
2014	0.00	39.78	0.00	0.00
2015	0.00	34.02	0.00	0.00
2016	0.00	39.83	0.00	0.00
2017	0.00	48.83	0.00	0.00
2018	0.00	40.85	0.00	0.00
2019	0.00	35.85	0.00	0.00

Weights

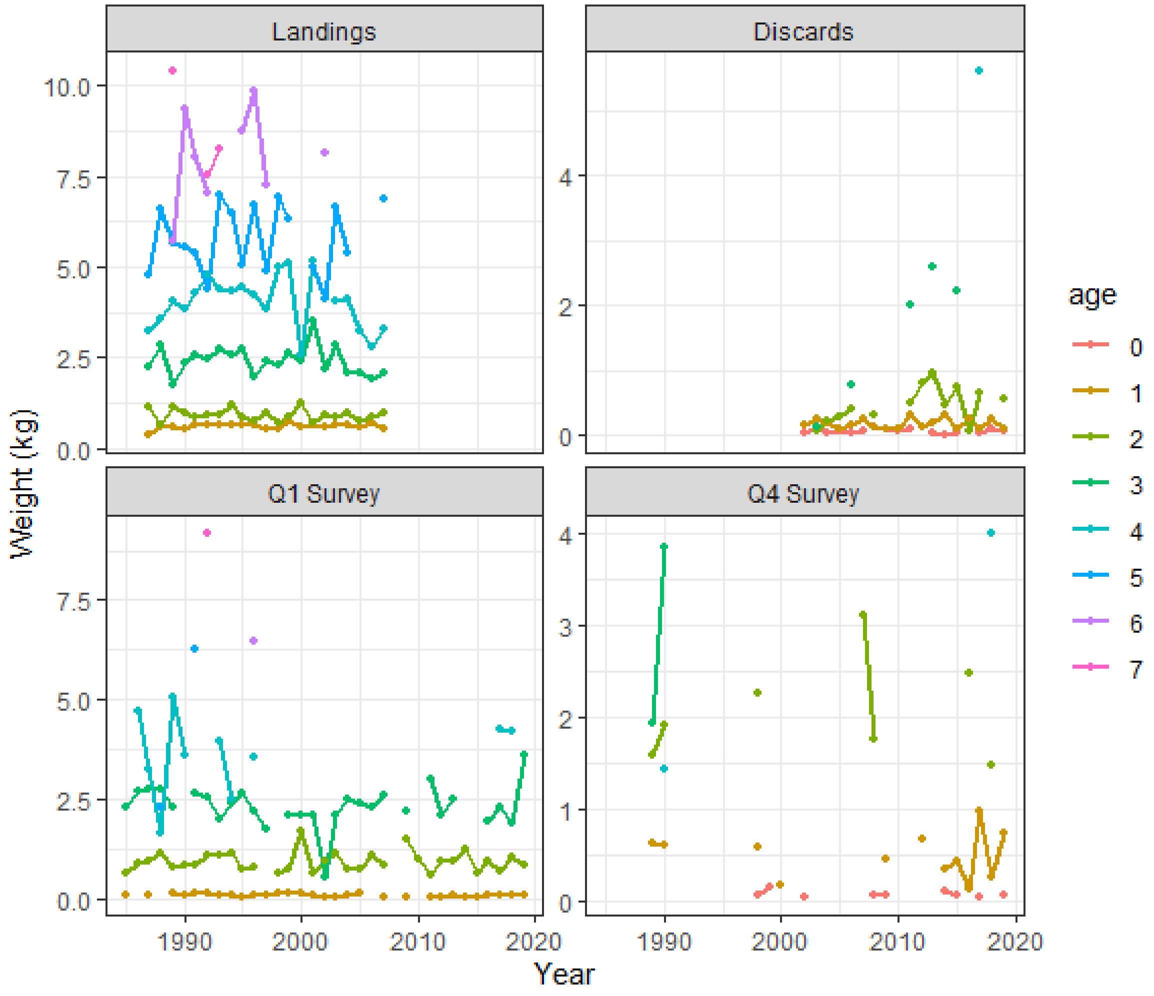


Figure A1. Mean weights at age from landings, discard and survey sampling. No clear trend in weights over time is apparent.

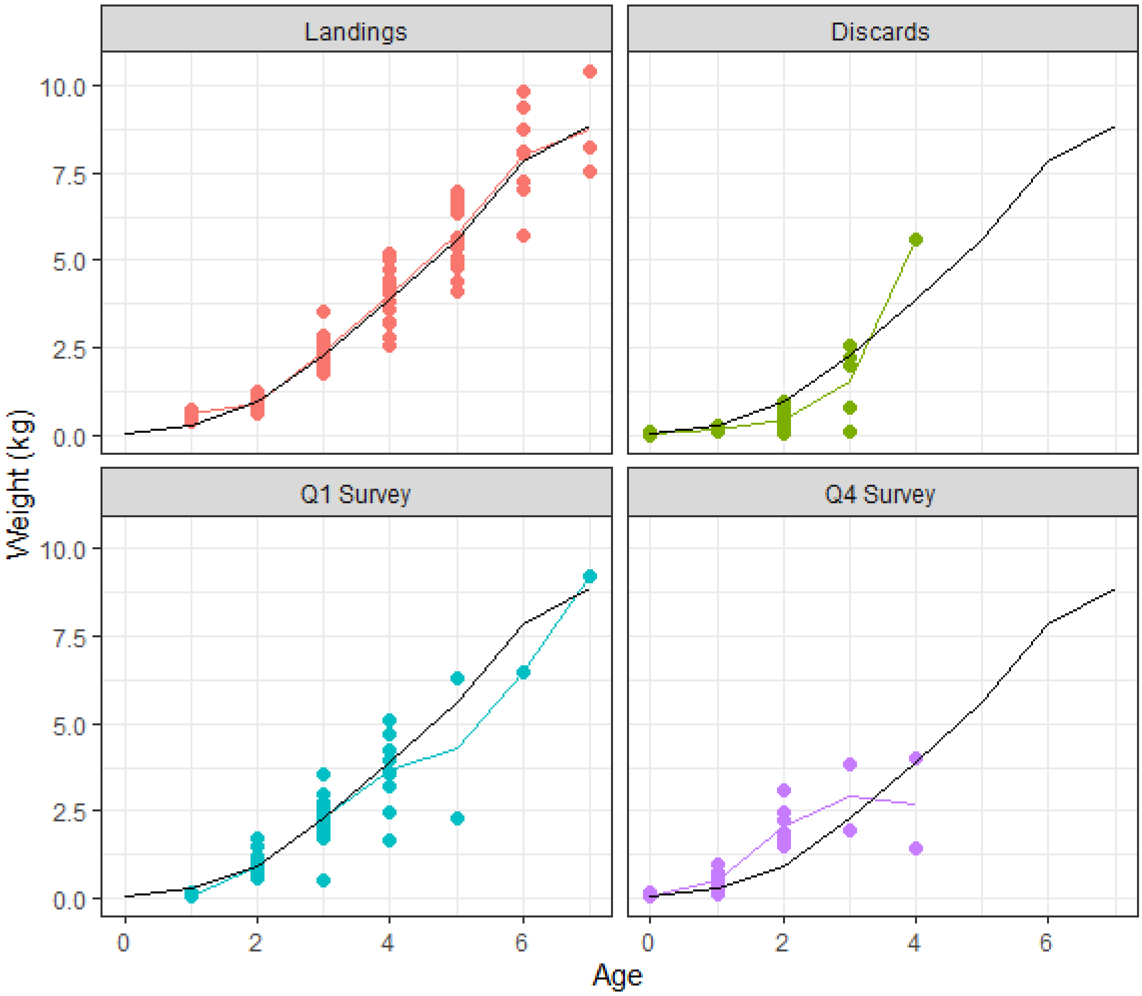


Figure A2. Weights at age for landings, discards and surveys. Coloured lines show the mean over all years for each category. Black line shows the average over all years and categories.

Table A 7 Weights at age (kg) used for all years in the assessment. Landings are the mean over all years for the landing category. Discard weights for ages 0-3 are the means over all years for that category. For ages 4 and older discard weights are the same as the stock weights. Stock weights are the means over all years and categories (including survey data).

Age	Landings	Discards	Stock
0		0.058	0.063
1	0.598	0.175	0.297
2	0.907	0.467	0.945
3	2.410	1.544	2.301
4	4.010	3.878	3.878
5	5.769	5.619	5.619
6	8.009	7.840	7.840
7	8.739	8.852	8.852

Appendix B: Age structured assessment model (ASM)

An age structured model is used to describe population change over time. The population and fishery equations are given in Table B1 where the numbers at age, *N*, decline as a result of a total mortality, *Z* (T1.1). The total mortality is the sum of natural mortality, *M*, and fishing mortality, *F* (T1.2). The fishing mortality is partitioned into an age effect or selectivity, *s*, and a year effect, *f*, that represents the overall annual fishing effort (T1.3). The selectivity of the fishery is described by a two-parameter gamma curve (T1.5) and is assumed to be the same for all fleets as there is incomplete data on the fishery age compositions (discard age compositions are absent until 2002) to estimate fleet specific selectivity. Fishing effort, *f* is disaggregated to allow different values of *f* by fleet, *g*, and follows a random walk(T1.4).

The observation equations describing how the catches and survey indices arise are given in Table B2. The survey indices, *u*, are assumed to be proportional to the population in the sea as a result of selectivity, *s*, and an overall catchability constant, *q* (T2.1). The selectivity of the survey is assumed to be logistic (T2.2). The fishery catches arise from the standard Baranov catch equation (T2.3) and are partitioned between landings, *l* and discards, *d*, using a logistic retention curve (T2.4 - T2.6). As the pattern of discarding changes over time, the parameters of the retention curve are modelled with a random walk (T2.7). We assume that the retention curve is the same for all fleets. The total landed and discard weight (*L* and *D*) is then simply a sum of products of numbers and mean weight-at-age (T2.8).

The sampling distribution assumptions are given in Table B3. The age compositions are modelled with a Dirichlet-Multinomial model (Thorson et al; 2017) and is applied the surveys, landings and discards (T3.1-T3.3). The total abundance in the surveys, *U*, is assumed log-normally distributed (T3.4). A similar assumption is made for the total landings and discards. (T3.5-6).

In the case of landings and discards there are zero values in recent years for some fleets. These need to be included in the likelihood but are undefined in a lognormal distribution. For zero values we assume that the probability of observing a zero value is a logistic function of the true value. Thus, for landings and discards we have:

$$prob\left(\hat{L}_{y,g} = 0 \middle| L_{y,g}\right) = 1 - \frac{1}{\left(1+\exp\left(\frac{2.197\left(z50-\log\left(L_{y,g}\right)\right)}{zr}\right)\right)} \qquad \text{(B1)}$$

$$prob\left(\hat{D}_{y,g} = 0 \middle| D_{y,g}\right) = 1 - \frac{1}{\left(1+\exp\left(\frac{2.197\left(z50-\log\left(D_{y,g}\right)\right)}{zr}\right)\right)} \qquad \text{(B2)}$$

Where z50 represents the value of *L* or *D* at 50% probability and zr is a measure of the slope of the logistic function.

Since non-zero values are described by a lognormal distribution, $g(\hat{x}|\theta)$, with parameters $\theta = (\log(x), \sigma)$ that represent the mean and standard deviation, the likelihood for all observations (where x, is either landings or discards) can then be written in the form:

$$\mathcal{L}(\hat{x}|\theta) = \left\{ \begin{matrix} prob(\hat{x} = 0|x),\ \hat{x} = 0 \\ prob(\hat{x} \neq 0|x)g(\hat{x}|\theta),\ \hat{x} \neq 0 \end{matrix} \right\} \qquad \text{(B3)}$$

Table B1. Population and fishery equations.

No.	Equation	Description
T1.1	$N_{a,y} = N_{a-1,y-1}e^{-Z_{a-1,y-1}}$	The population N at age a and year y decays exponentially with total mortality Z.
T1.2	$Z_{a,y} = M_{a,y} + \sum_g F_{a,y,g}$	The total mortality Z is partitioned between natural mortality M, and fishing mortality F, where g is an index for fleet. Natural mortality is assumed to be known.
T1.3	$F_{a,y,g} = s_a f_{y,g}$	Fishing mortality is separable into an age effect (selectivity), *s*, and year effect, *f*.
T1.4	$f_{y,g} \sim lognormal(\log(f_{y-1,g}), \sigma^f)$	The year effect, *f*, follows a random walk with lognormal process error, σ^f.
T1.5	$s_a = \left(\frac{a}{(\alpha-1)\beta}\right)^{(\alpha-1)} e^{\alpha-1-\frac{a}{\beta}}$ Where $mode = \beta(\alpha - 1)$	Selectivity is described by a gamma curve with parameters α and β and is fixed over the full time period for both fleets. The mode occurs at maximum selection.

Table B2. Observation equations

No.	Equation	Description
T2.1	$u_{a,y,i}=s_{a,i}q_iN_{a,y}\exp\left(-\rho_iZ_{a,y}\right)$ $U_{y,i}=\sum_a u_{a,y,i}$ $\pi_{a,y,i}=\frac{u_{a,y,i}}{U_{y,i}}$	The index of abundance at age, $u_{a,y,i}$, from the *ith* survey is proportional to population size where the proportionality is the product of age specific selectivity, $s_{a,i}$, and an overall survey catchability q_i. The exponential term accounts for mortality during the year up to the time of the survey where ρ is the proportion of the year elapsed before the survey. $U_{y,i}$ is the total number of fish in the annual index and π is the proportion of fish at age in the index.
T2.2	$s_{a,i}=\frac{1}{\left(1+\exp\left(\frac{2.197(s50_i-a)}{sr_i}\right)\right)}$	Age specific survey selectivity is described by a logistic function with parameters *s50* and *sr.*
T2.3	$c_{a,y,g}=F_{a,y,g}N_{a,y}(1-e^{-Z_{a,y}})/Z_{a,y}$	The catch at age, c, is given by the Baranov equation where g indexes fleet (gear)
T2.4	$l_{a,y,g}=p_{a,y}c_{q,y,g}$ $\pi^l_{a,y,g}=\frac{l_{a,y,g}}{\sum_a l_{a,y,g}}$	The landings at age, *l*, are proportion, *p*, of the catch where *g* indexes fleet and π^l is the proportion of fish at age *a* in the landings.
T2.5	$d_{a,y,g}=(1-p_{a,y})c_{a,y,g}$ $\pi^d_{a,y,g}=\frac{d_{a,y,g}}{\sum_a d_{a,y,g}}$	The discards at age, d, are a proportion, *(1-p)* of the catch and π^d is the proportion of fish at age *a* in the discards.
T2.6	$p_{a,y}=\frac{1}{\left(1+\exp\left(\frac{2.197(d50_y-a)}{dr_y}\right)\right)}$	The proportion of catch landed is a logistic function of age with parameters, *d50* and *dr* that represent the 50% retention age and selection range.
T2.7	$d50_y\sim lognormal(\log(d50_{y-1}),\sigma^{d50})$ $dr_y\sim lognormal(\log(dr_{y-1}),\sigma^{dr})$	The parameters of the retention curve follow a random walk
T2.8	$L_{y,g}=\sum_a w_{l,a,y,g}\,l_{a,y,g}$ $D_{y,g}=\sum_a w_{d,a,y,g}\,d_{a,y,g}$	The total weight landed or discarded by fleet, *L* and *D*, is the sum of over ages of numbers times mean weight at age, *w*.

Table B3. Sampling distributions

No.	Equation	Description
T3.1	$\hat{\boldsymbol{u}}_{\boldsymbol{y},\boldsymbol{i}} \sim DirMult\left(v_i^u, \boldsymbol{\gamma}_{\boldsymbol{y},\boldsymbol{i}}\right)$ where $\hat{\boldsymbol{u}}_{\boldsymbol{y},\boldsymbol{i}} = \left(\hat{u}_{1,y,i}, \hat{u}_{2,y,i}, \hat{u}_{3,y,i} \ldots.\right)$ $\boldsymbol{\gamma}_{\boldsymbol{y},\boldsymbol{i}} = \left(\pi_{1,y,i}, \pi_{2,y,i}, \pi_{3,y,i} \ldots.\right)\Phi_i^u$ $v_i^u = \sum_a \hat{u}_{a,y,i}$	The vector of observed numbers at age in the survey index, $\hat{\boldsymbol{u}}$, normalised to the sample size, *v,* is drawn from a Dirichlet-multinomial distribution with a parameter vector, $\boldsymbol{\gamma}$. The parameter vector is a product of the proportions at age and a dispersion parameter, Φ_i^u.
T3.2	$\hat{\boldsymbol{l}}_{\boldsymbol{y},\boldsymbol{g}} \sim DirMult\left(v_g^l, \boldsymbol{\gamma}_{\boldsymbol{y},\boldsymbol{g}}\right)$ where $\hat{\boldsymbol{l}}_{\boldsymbol{y},\boldsymbol{g}} = \left(\hat{l}_{1,y,g}, \hat{l}_{2,y,g}, \hat{l}_{3,y,g} \ldots.\right)$ $\boldsymbol{\gamma}_{\boldsymbol{y},\boldsymbol{g}} = \left(\pi_{1,y,g}^l, \pi_{2,y,g}^l \pi_{3,y,g}^l \ldots.\right)\Phi_g^l$ $v_g^l = \sum_a \hat{l}_{a,y,g}$	The vector of observed numbers at age in the landings, $\hat{\boldsymbol{l}}_{\boldsymbol{y},\boldsymbol{g}}$ **,** normalised to the sample size, *v*, is drawn from a Dirichlet-multinomial distribution with a parameter vector, $\boldsymbol{\gamma}_{\boldsymbol{y},\boldsymbol{g}}$**.** The parameter vector is a product of the proportions at age and a dispersion parameter, Φ_g^l.
T3.3	$\hat{\boldsymbol{d}}_{\boldsymbol{y},\boldsymbol{g}} \sim DirMult\left(v_g^d, \boldsymbol{\gamma}_{\boldsymbol{y},\boldsymbol{g}}\right)$ where $\hat{\boldsymbol{d}}_{\boldsymbol{y},\boldsymbol{g}} = \left(\hat{d}_{1,y,g}, \hat{d}_{2,y,g}, \hat{d}_{3,y,g} \ldots.\right)$ $\boldsymbol{\gamma}_{\boldsymbol{y},\boldsymbol{g}} = \left(\pi_{1,y,g}^d, \pi_{2,y,g}^d \pi_{3,y,g}^d \ldots.\right)\Phi_g^d$ $v_g^d = \sum_a \hat{d}_{a,y,g}$	The vector of observed numbers at age in the discards, $\hat{\boldsymbol{d}}_{\boldsymbol{y},\boldsymbol{g}}$ **,** normalised to the sample size, *v*, is drawn from a Dirichlet-multinomial distribution with a parameter vector, $\boldsymbol{\gamma}_{\boldsymbol{y},\boldsymbol{g}}$**.** The parameter vector is a product of the proportions at age and a dispersion parameter, Φ_g^d.
T3.4	$\hat{U}_{\boldsymbol{y},\boldsymbol{i}} \sim lognormal(log\left(U_{y,i}\right), \sigma_i^U)$	The observed total abundance in the survey, $\hat{U}_{\boldsymbol{y},\boldsymbol{i}}$, is lognormally distributed with mean $log\left(U_{y,i}\right)$ and standard deviation σ_i^u.
T3.5	$\hat{L}_{\boldsymbol{y},\boldsymbol{g}} \sim lognormal(log\left(L_{y,g}\right), \sigma_g^L)$	The observed landed biomass, $\hat{L}_{\boldsymbol{y},\boldsymbol{g}}$, is lognormally distributed with mean $log\left(L_{y,g}\right)$and standard deviation*,* σ_g^L*.*
T3.6	$\hat{D}_{\boldsymbol{y},\boldsymbol{g}} \sim lognormal(log\left(D_{y,g}\right), \sigma_g^D)$	The observed discarded biomass, $\hat{D}_{\boldsymbol{y},\boldsymbol{g}}$, is lognormally distributed with mean $log\left(D_{y,g}\right)$and standard deviation*,* σ_g^D.

Table B4. Priors on the parameters.

$Log(N_{1,y}) \sim uniform(-10{,}20)$
$Log(N_{a,1}) \sim uniform(-10{,}20)$
$f_{1,g} \sim uniform(0{,}2)$
$\alpha \sim uniform(1{,}20)$
$mode \sim uniform(0{,}6)$
$\log\,(q_i) \sim uniform(-10{,}10)$
$s50 \sim uniform(-1{,}6)$
$sr \sim uniform(0{,}3)$
$d50_1 \sim uniform(0{,}6)$
$dr_1 \sim uniform(0.1{,}5)$
$\theta_i^u \sim uniform(1{,}1000)$
$\theta_g^l \sim uniform(1{,}1000)$
$\theta_g^d \sim uniform(1{,}1000)$
$p50 \sim uniform(-2{,}10)$
$pr \sim uniform(-2{,}3)$
$\sigma^f \sim uniform(0{,}1)$
$\sigma^{d50} \sim uniform(0{,}1)$
$\sigma^{dr} \sim uniform(0{,}1)$
$\sigma_i^u \sim uniform(0.2{,}10)$
$\sigma_g^l \sim uniform(0.2{,}1)$
$\sigma_g^d \sim uniform(0.2{,}10)$

Appendix C: Base model fit

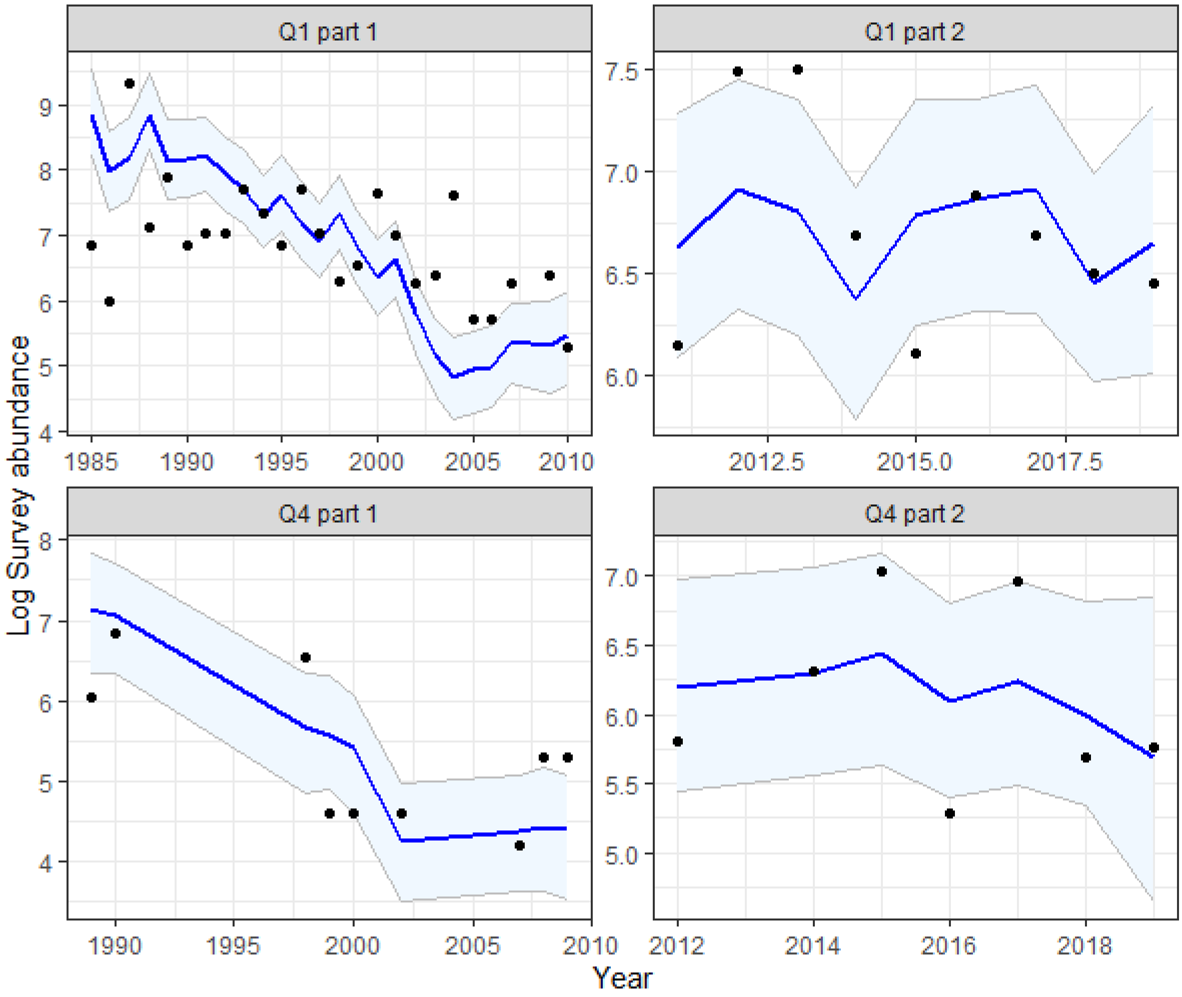


Figure C1. Base model fit to the survey abundance data. Solid line shows the median value and the shaded area the 95% credible intervals. Dots show the observations.

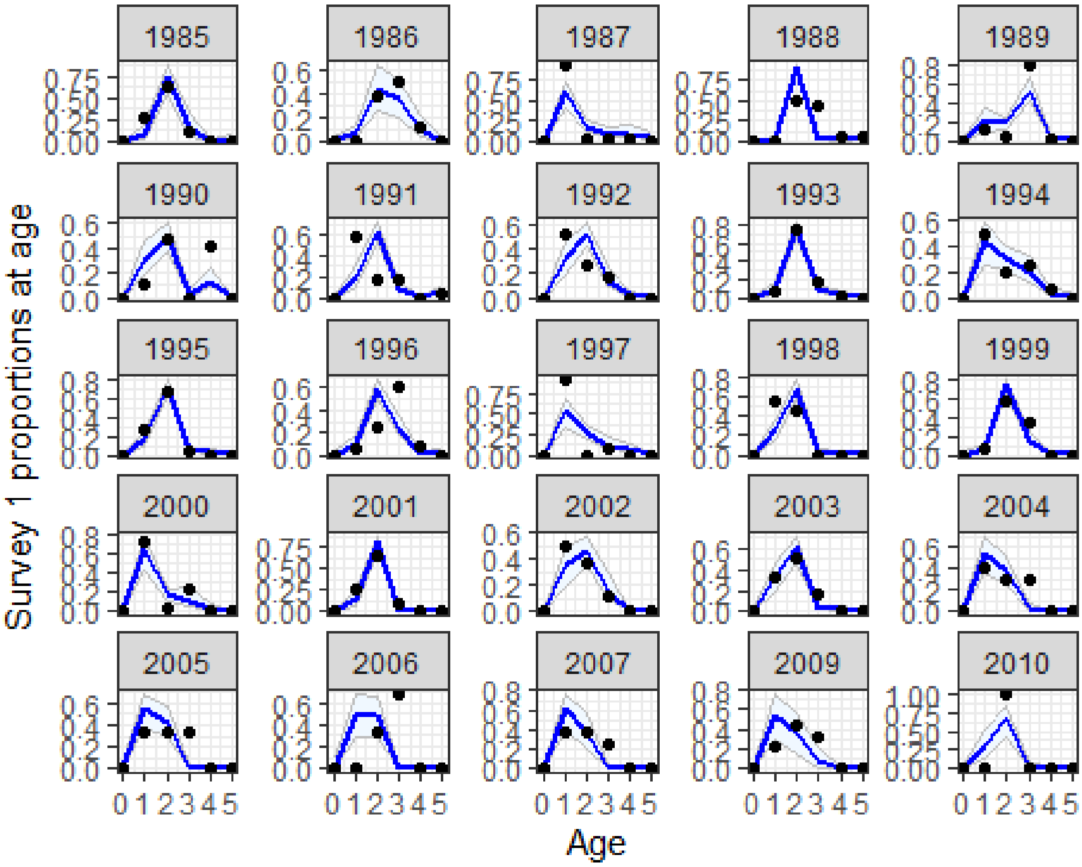


Figure C2. Survey Q1 part 1. Base model fit to the proportions at age. Solid line shows the median value and the shaded area the 95% credible intervals. Dots show the observations.

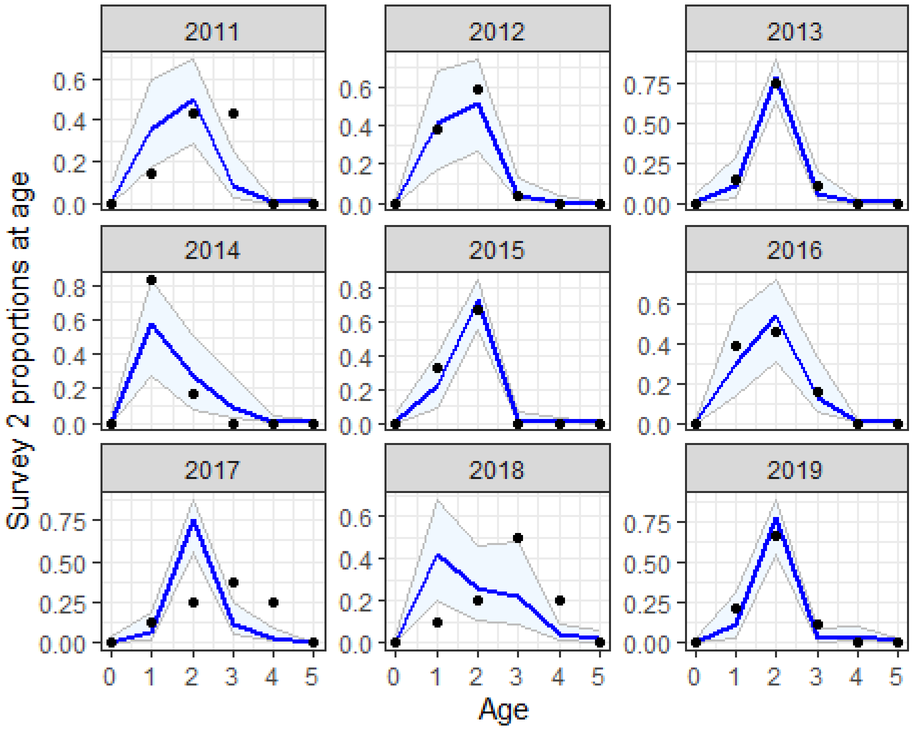


Figure C3. Survey Q1 part 2. Base model fit to the proportions at age. Solid line shows the median value and the shaded area the 95% credible intervals. Dots show the observations.

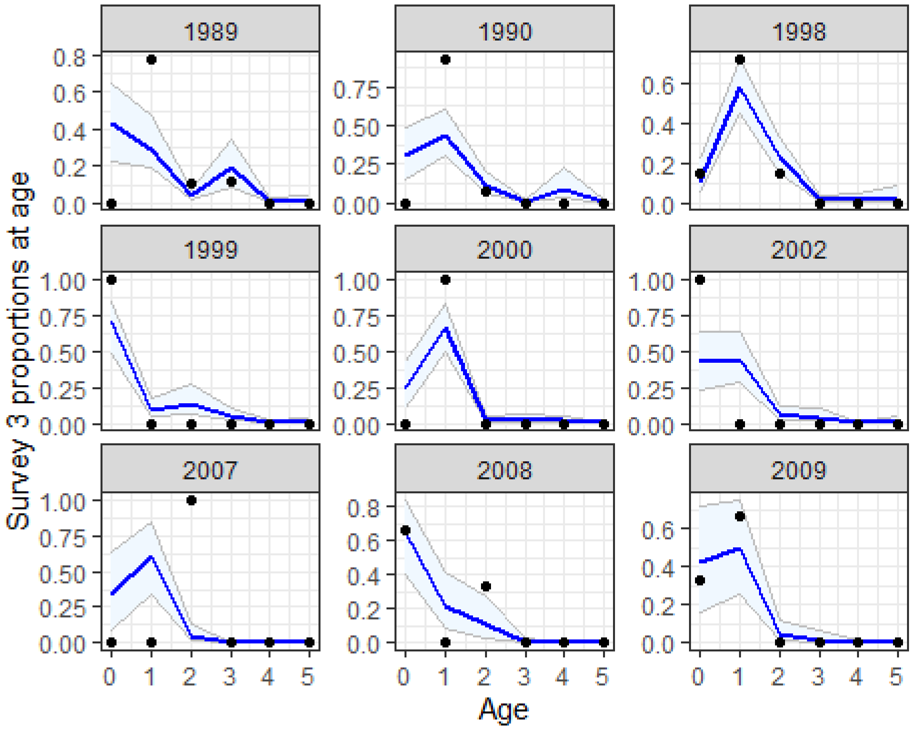


Figure C4. Survey Q4 part 1. Base model fit to the proportions at age.Solid line shows the median value and the shaded area the 95% credible intervals. Dots show the observations.

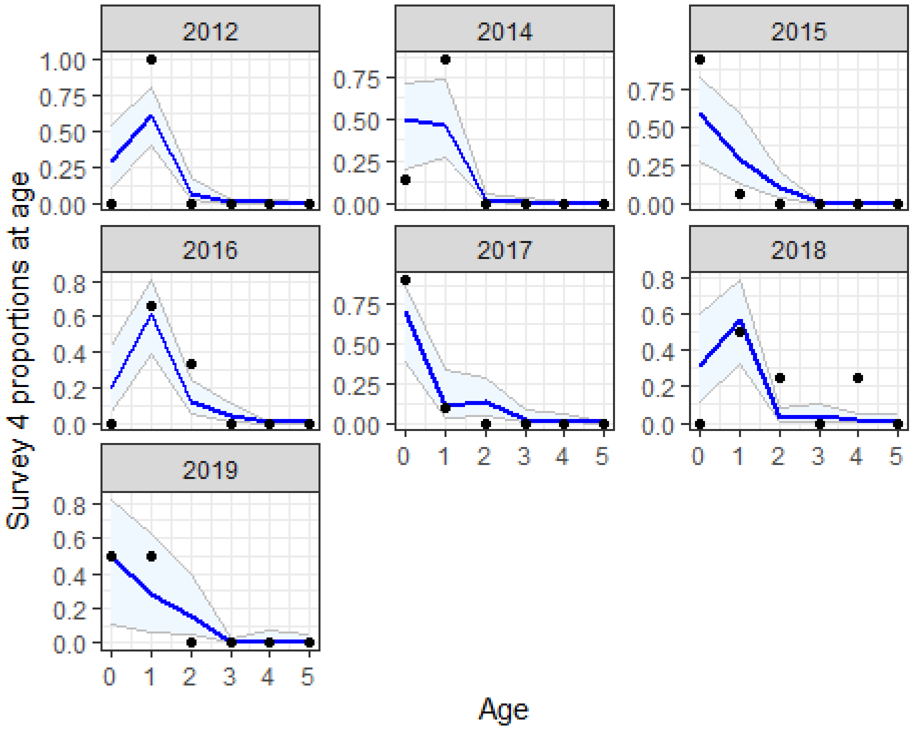


Figure C5. Survey Q4 part 2. Base model fit to proportions at age. Solid line shows the median value and the shaded area the 95% credible intervals. Dots show the observations.

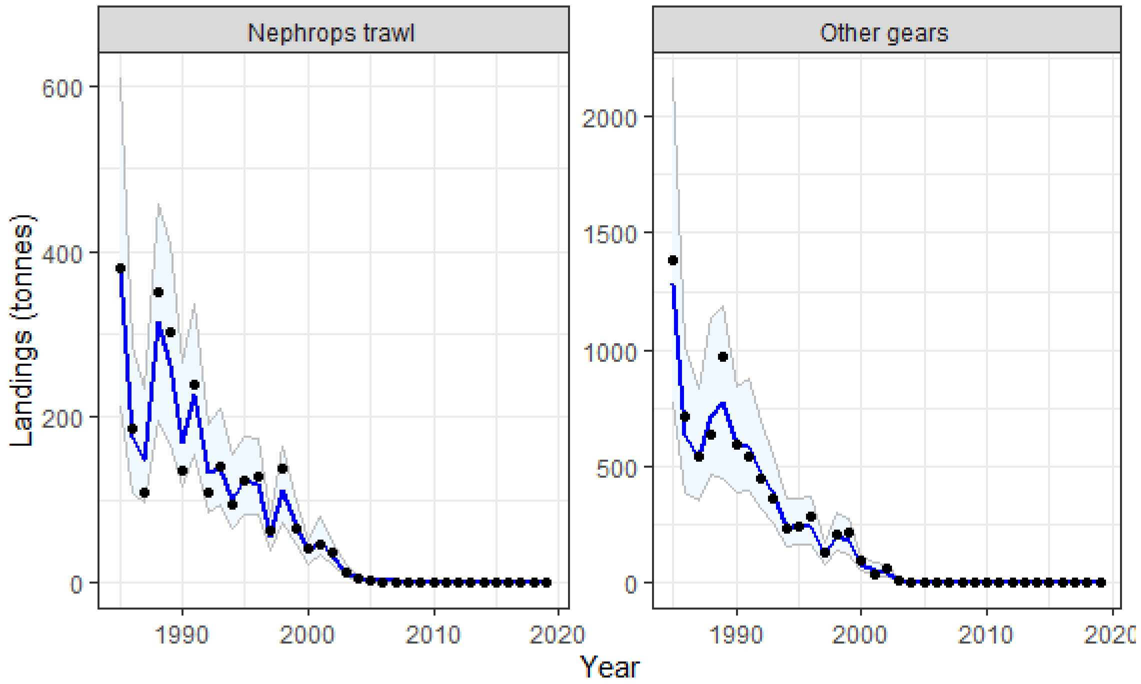


Figure C6. Base model fit to the total landings by fleet. Solid line shows the median value and the shaded area the 95% credible intervals. Dots show the observations.

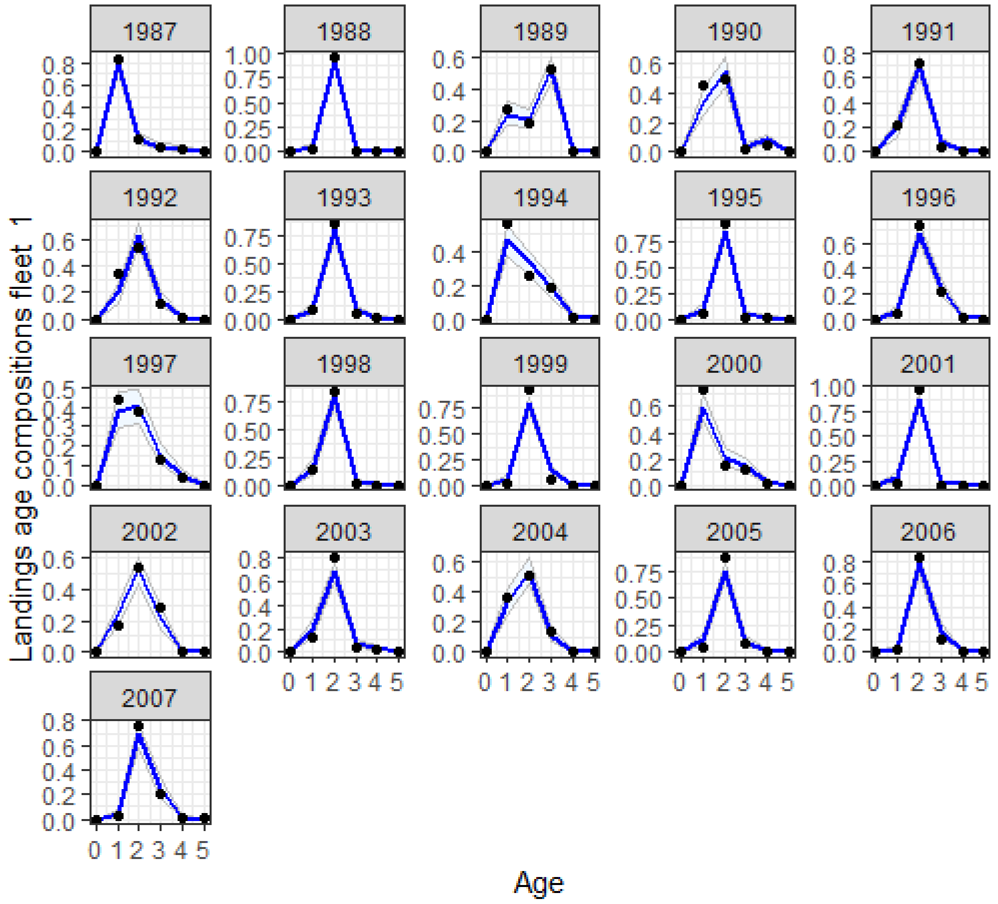


Figure C7. Base model fit to Nephrops trawl landings age compositions. Solid line shows the median value and the shaded area the 95% credible intervals. Dots show the observations.

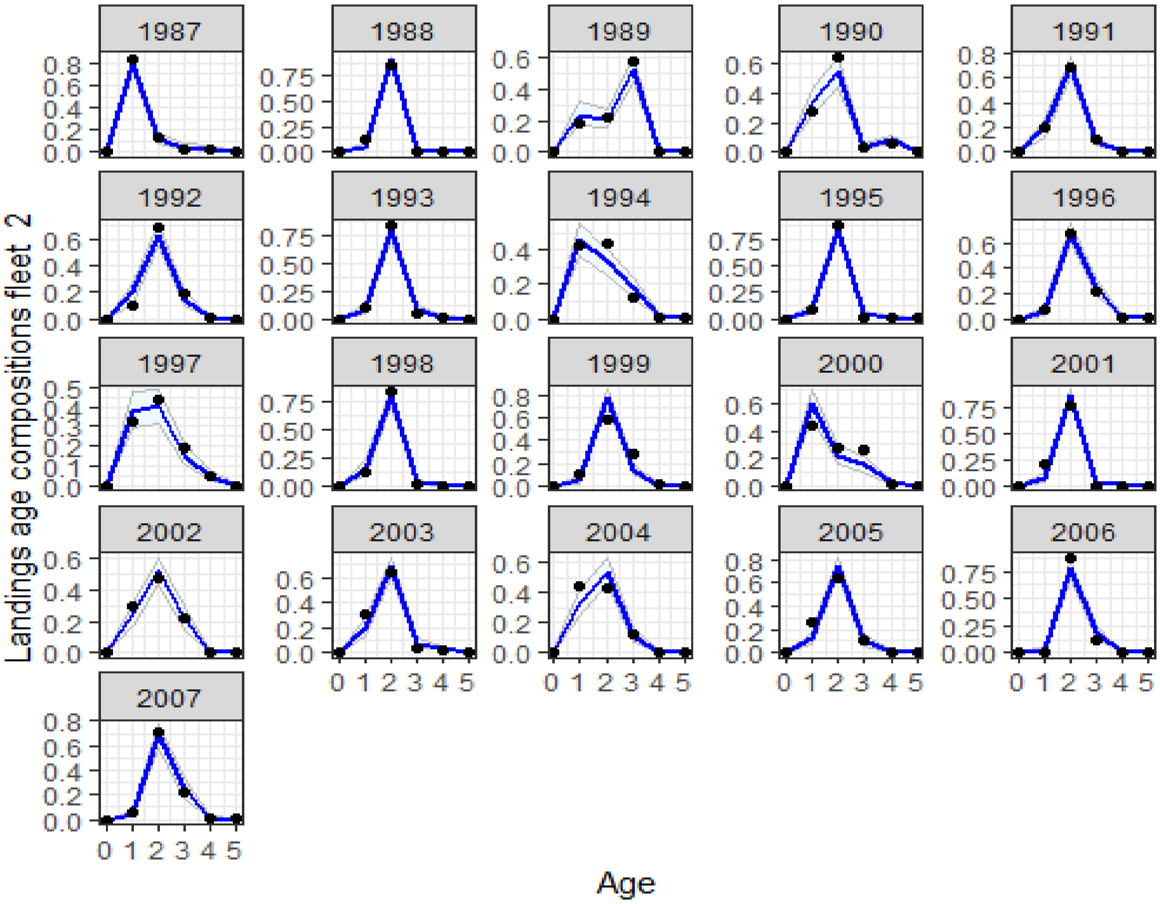


Figure C8. Base model fit to Other gears landings age compositions. Solid line shows the median value and the shaded area the 95% credible intervals. Dots show the observations.

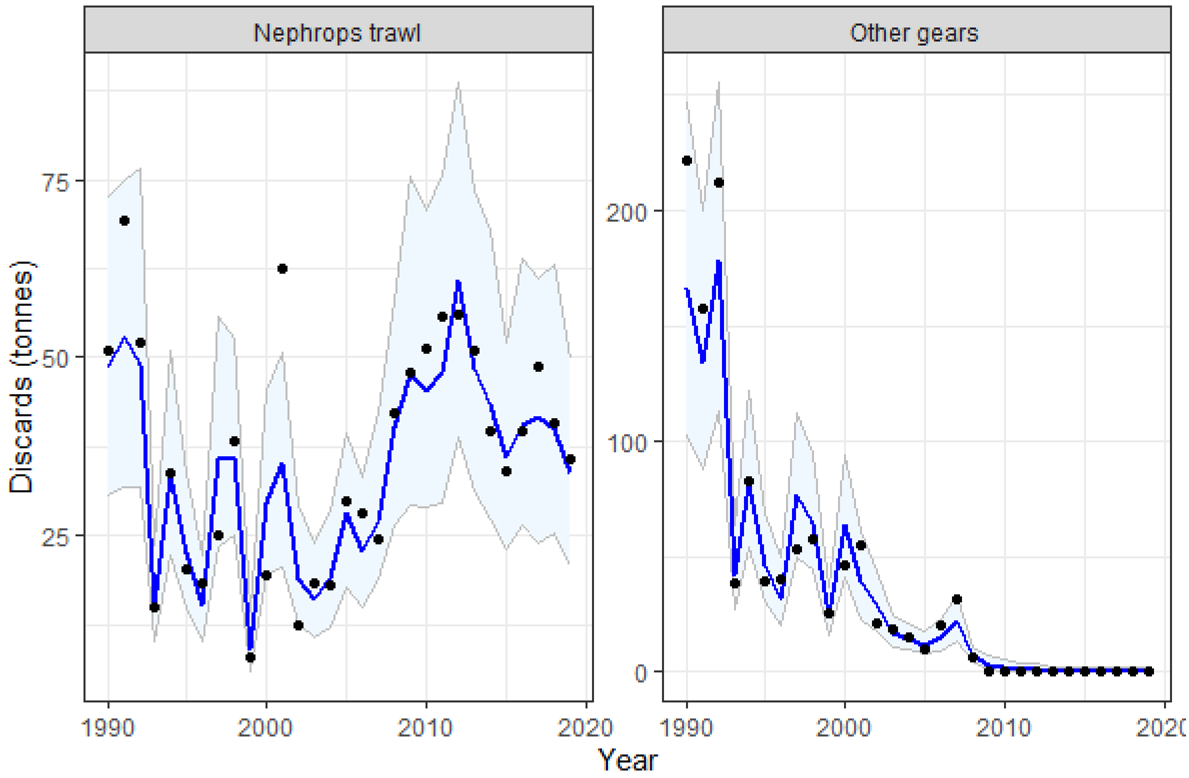


Figure C9. Base model fit to total discard weight. Solid line shows the median value and the shaded area the 95% credible intervals. Dots show the observations.

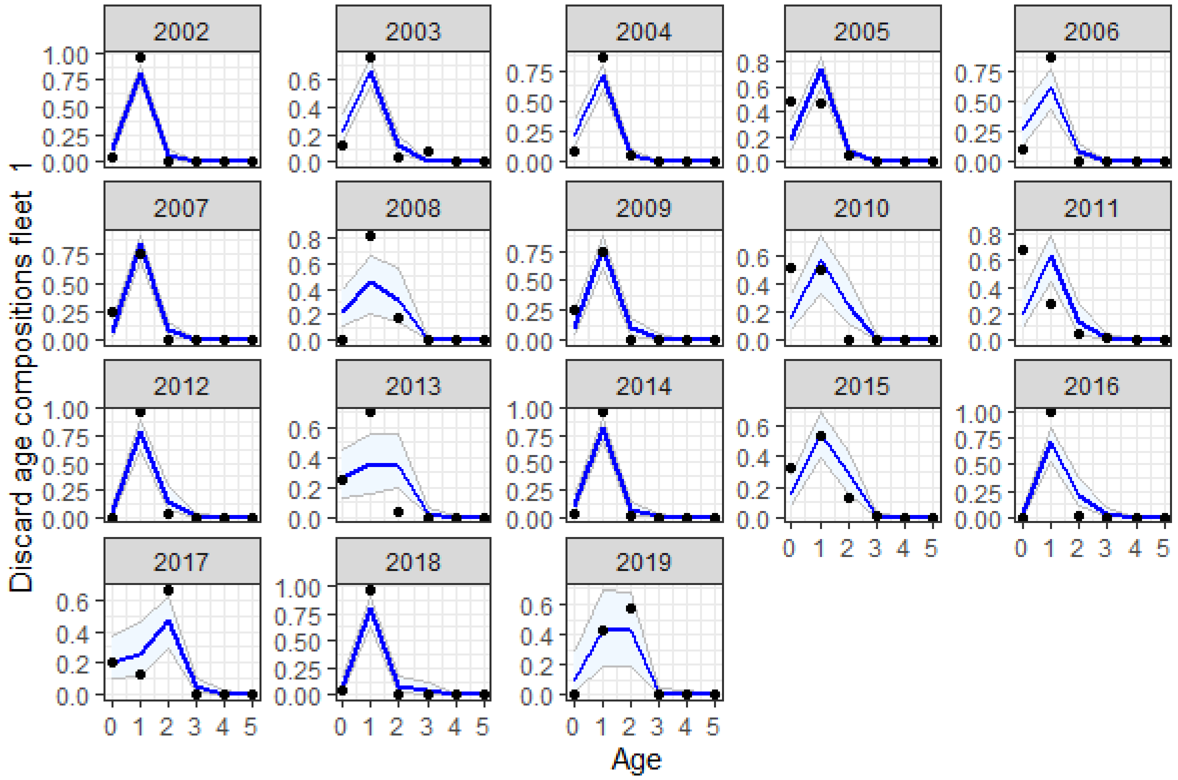


Figure C10. Base model fit to Nephrops trawl discard age compositions. Solid line shows the median value and the shaded area the 95% credible intervals. Dots show the observations.

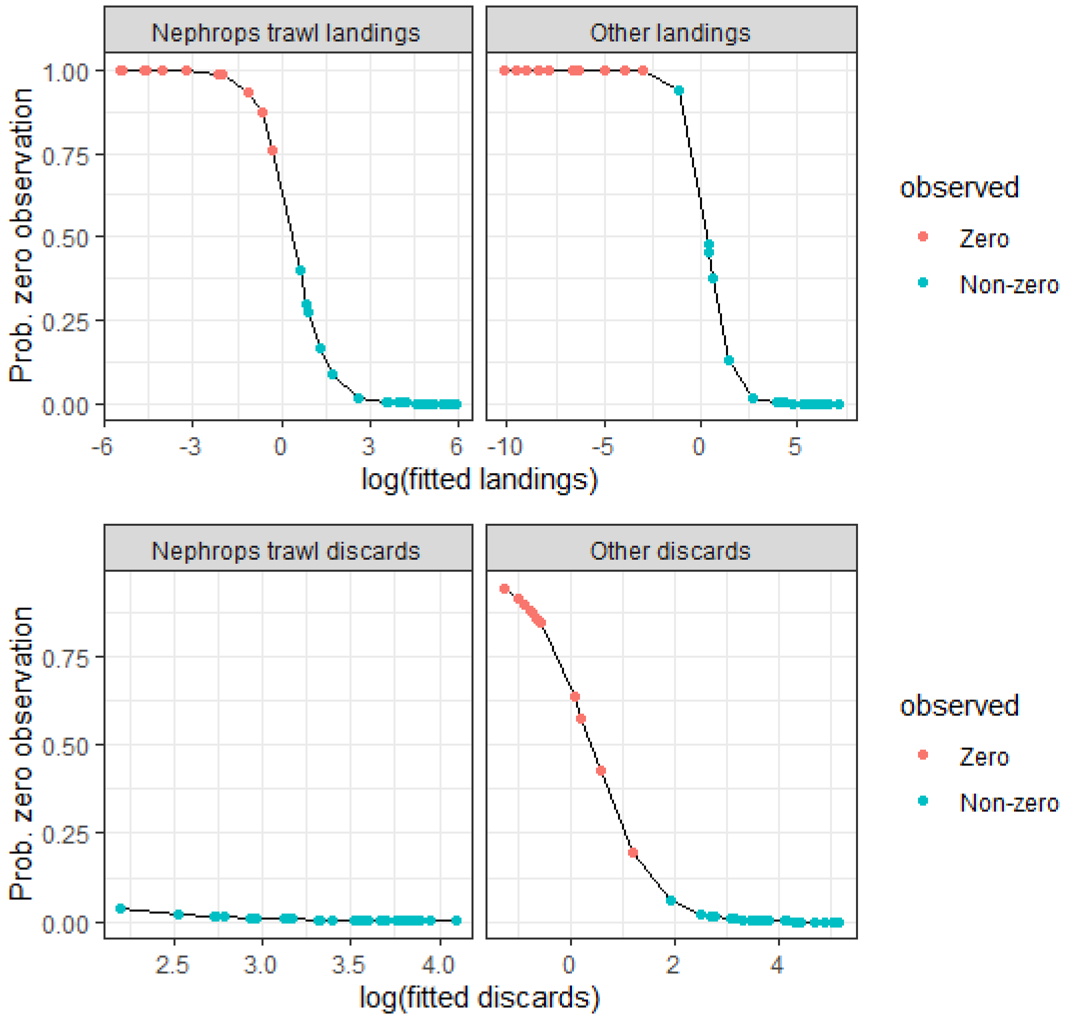


Figure C11. ASM model. The probability of observing a zero value given the true value of landings or discards. The logistic curve is the same for each fleet and catch category. Dots indicate where the observed zeros (red) or non-zero values (blue) occur given the expected catch. Zero values occur where the predicted probability is high.

Appendix D: Surplus Production Model (SPM)

Data

Available data comprise survey biomass indices, landings and discards by fleet (Table D1). There are two time series of survey data, one for quarter 1 and the other in quarter 4. A change of survey design occurred in 2011 with shorter tows and modified ground gear. Consequently, each survey is split into two, "old" and "new".

Surplus Production Model (SPM)

For biomass, B, the standard delay-difference equation for the Schaefer model can be written:

$$B_{t+1} = \left(B_t \left[1 + r\left(1 - \frac{B_t}{B_0}\right)\right] - F_t B_t\right) \exp\left(e_t\right) \qquad \text{(D1)}$$

Where *t* is a subscript for year and;

B_0 is the maximum biomass the environment can support (unexploited biomass),
r represents the intrinsic rate of increase in biomass,
F is the fishing mortality (or yield-biomass ratio), and
e_t is a random effect drawn from a normal distribution with zero mean and standard deviation , sd_B and represents process noise to account for events such as recruitment variation.

For k fleets, each with fleet fishing mortality, f_k , the total fishing mortality is the sum:

$$F_t = \sum_k f_{k,t} \qquad \text{(D2)}$$

Where the catch by fleet, y, is given by:

$$y_{k,t} = f_{k,t} B_t \qquad \text{(D3)}$$

And the total catch, Y, is the sum over fleets:

$$Y_t = B_t \sum_k f_{k,t} \qquad \text{(D4)}$$

For each fleet the fishing mortality follows a random walk with standard deviation sd^f;

$$\log\left(f_{k,t}\right) \sim normal\left(\log\left(f_{k,t-1}\right), sd_k^f\right) \qquad \text{(D5)}$$

The catch by fleet, *y,* can be split into landings, *l*, and discards, *d*, where *p* represents the proportion landed:

$$l_{k,t} = p_{k,t} y_{k,t} \qquad \text{(D6)}$$

$$d_{k,t} = y_{k,t} - l_{k,t} \qquad \text{(D7)}$$

The proportion landed changes over time and follows a random walk on a logit scale:

$$logit(p_{k,t}) \sim normal(logit(p_{k,t-1}), sd_k^p) \qquad \text{(D8)}$$

We assume any survey indices, u, are proportional to the stock biomass. For the *jth* survey:

$$u_{j,t} = q_j B_t \qquad \text{(D9)}$$

The observed quantities, landings, discards and biomass indices, are assumed to have lognormal error distributions for non-zero values, i.e.

$$\hat{l}_{k,t} \sim lognormal(\log(l_{k,t}), sd_k^l) \qquad \text{(D10)}$$

$$\hat{d}_{k,t} \sim lognormal(\log(d_{k,t}), sd_k^d) \qquad \text{(D11)}$$

$$\hat{u}_{j,t} \sim lognormal(\log(u_{j,t}), sd_j^u) \qquad \text{(D12)}$$

In the case of landings and discards there are zero values in recent years for some fleets. These need to be included in the likelihood but are undefined in a lognormal distribution. For zero values we assume that the probability of observing a zero value is a logistic function of the true value. Thus, for landings and discards we have:

$$prob(\hat{l}_{k,t} = 0 | l_{k,t}) = 1 - \frac{1}{\left(1+\exp\left(\frac{2.197(z50-\log(l_{k,t}))}{zr}\right)\right)} \qquad \text{(D13)}$$

$$prob(\hat{d}_{k,t} = 0 | d_{k,t}) = 1 - \frac{1}{\left(1+\exp\left(\frac{2.197(z50-\log(d_{k,t}))}{zr}\right)\right)} \qquad \text{(D14)}$$

Where z50 and zr represent the value of *l* or *d* at 50% probability and zr is a measure of the slope of the logistic function.

If non-zero observed values are described by a lognormal distribution, $g(\hat{x}|\theta)$, with parameters $\theta = (\log(x), \sigma)$ that represent the mean and standard deviation, the likelihood for all observations (where x, is either landings or discards) can then be written in the form:

$$\mathcal{L}(\hat{x}|\theta) = \begin{Bmatrix} prob(\hat{x} = 0|x), \ \hat{x} = 0 \\ prob(\hat{x} \neq 0|x) g(\hat{x}|\theta), \ \hat{x} \neq 0 \end{Bmatrix} \qquad \text{(D15)}$$

Parameter estimation

For convenience, the model is parameterised in terms of maximum sustainable fishing mortality, F_{MSY} rather than r, (noting r=2 F_{MSY}). Parameter estimation was performed using the Bayesian package “rstan” with priors on the parameters (Table D2). Most priors were uniform. The beta distribution prior on F_{MSY} is based on a meta-analysis reported in

Sparholt et al (2021) and has a mode of approximately 0.3. The square root prior on B_0 was found to cause less bias in the estimate (Cook *et al*, 2021).

The model was fitted with three MCMC chains running for 30,000 iterations, a burn-in of 15,000 and a thinning rate of 150. Convergence was assessed from trace plots and the Rhat statistic.

Results

The model fits the survey trends but there are clearly large residuals which is likely due to measurement error (Figure D1). The landings and discard data are fit very closely (Figure D2). Observed zero catches are estimated to occur with high probability (>0.5) when the underlying true catch falls below 3 tonnes; z50=1.11 (Figure D3). Stock summary statistics are shown in Figure D4. Biomass shows a long term decline with exploitation very high. A retrospective analysis is shown in Figure D5. There appears to be a tendency to over-estimate the yield/biomass ratio, but this is low in the recent 3 years.

References

Cook, R. M., E. Acheampong, J. Aggrey-Fynn, and M. Heath. 2021. A fleet based surplus production model that accounts for increases in fishing power with application to two west African pelagic stocks. Fisheries Research 243: 106048. https://doi.org/10.1016/j.fishres.2021.106048.

Sparholt H, Bogstad B, Christensen V et al. (2021).Estimating FMSY from an ensemble of data sources to account for density dependence in Northeast Atlantic fish stocks. ICES Journal Marine Science. 78:55–69. 10.1093/icesjms/fsaa175.

Table D1. Survey and catch data for cod in the Clyde. Landings and discards are in tonnes. Surveys are relative biomass per hour. NA indicates not available.

	Surveys		Landings		Discards	
Year	Q1	Q4	*Nephrops* trawl	Other gears	*Nephrops* trawl	Other gears
1985	6.19	NA	380.55	1382.35	NA	NA
1986	9.03	NA	187.22	712.77	NA	NA
1987	23.68	NA	109.85	539.91	NA	NA
1988	34.30	NA	350.17	638.60	NA	NA
1989	47.83	NA	303.53	974.05	NA	NA
1990	27.00	NA	136.44	592.16	51.03	221.46
1991	11.27	NA	239.87	544.67	69.18	157.08
1992	13.82	NA	109.93	447.90	52.12	212.37
1993	27.79	NA	140.79	365.61	14.80	38.43
1994	17.46	NA	95.14	233.57	33.70	82.73
1995	6.33	NA	125.05	245.69	20.18	39.65
1996	45.21	NA	129.66	284.95	18.25	40.10
1997	2.46	NA	63.23	134.38	24.96	53.04
1998	1.88	5.07	138.33	207.68	38.29	57.49
1999	8.20	0.15	67.23	218.72	7.83	25.48
2000	13.13	0.17	41.55	98.56	19.35	45.90
2001	6.63	NA	46.02	40.21	62.52	54.64
2002	2.30	0.04	38.05	63.94	12.42	20.87
2003	5.54	NA	13.41	13.50	18.42	18.54
2004	20.98	0.29	4.99	4.03	18.02	14.56
2005	3.26	NA	3.51	1.17	29.98	10.01
2006	5.62	NA	1.65	1.19	28.29	20.27
2007	5.23	2.01	1.83	2.36	24.55	31.58
2008	NA	1.21	1.82	0.26	42.32	5.93
2009	8.28	0.61	0.00	0.00	47.90	0.00
2010	1.98	NA	0.00	0.00	51.27	0.00
2011	7.15	NA	0.00	0.00	55.74	0.00
2012	9.32	2.13	0.00	0.00	56.10	0.00
2013	17.61	NA	0.00	0.00	51.00	0.00
2014	1.94	1.47	0.00	0.00	39.78	0.00
2015	1.99	0.89	0.00	0.00	34.02	0.00
2016	7.32	1.74	0.00	0.00	39.83	0.00
2017	16.82	1.27	0.00	0.00	48.83	0.00
2018	8.78	3.14	0.00	0.00	40.85	0.00
2019	6.12	1.24	0.00	0.00	35.85	0.00

Table D2. Priors on parameters to be estimated in the model.

Parameter	Prior	Definition
$\sqrt{B_0}$	uniform(10,70)	Unexploited biomass
F_{MSY}	beta(2,3)	Maximum sustainable fishing mortality
B_1	uniform(0.1,3850)	Initial biomass
q_j	uniform(0,20)	Survey catchability
sd_j^u	uniform(0,10)	Observation error for surveys
sd_k^l	uniform(0,10)	Observation error for landings
sd_k^d	uniform(0,10)	Observation error for discards
sd_k^p	uniform(0,10)	Process error for proportion landed
$z50$	uniform(1,100)	Logistic curve parameter for probability of a zero observation.
zr	uniform(1,100)	Logistic curve parameter for probability of a zero observation.
sd_k^f	uniform(0,1)	Process error for fishing mortality
sd_B	uniform(0,1)	Process error for biomass
$f_{1,k}$	uniform(0,3)	Initial fishing mortality
$logit(p_{1,k})$	uniform(-100,100)	Initial proportion landed

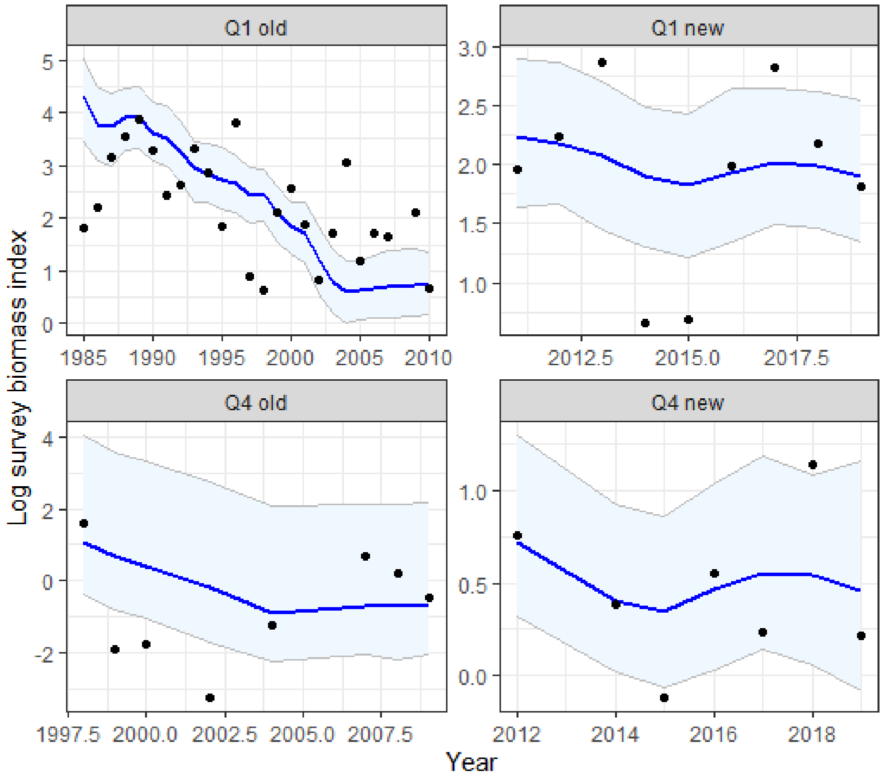


Figure D1. SPM Model fit to the survey indices. Solid line shows the median value and the shaded area the 95% credible intervals. Dots show the observations.

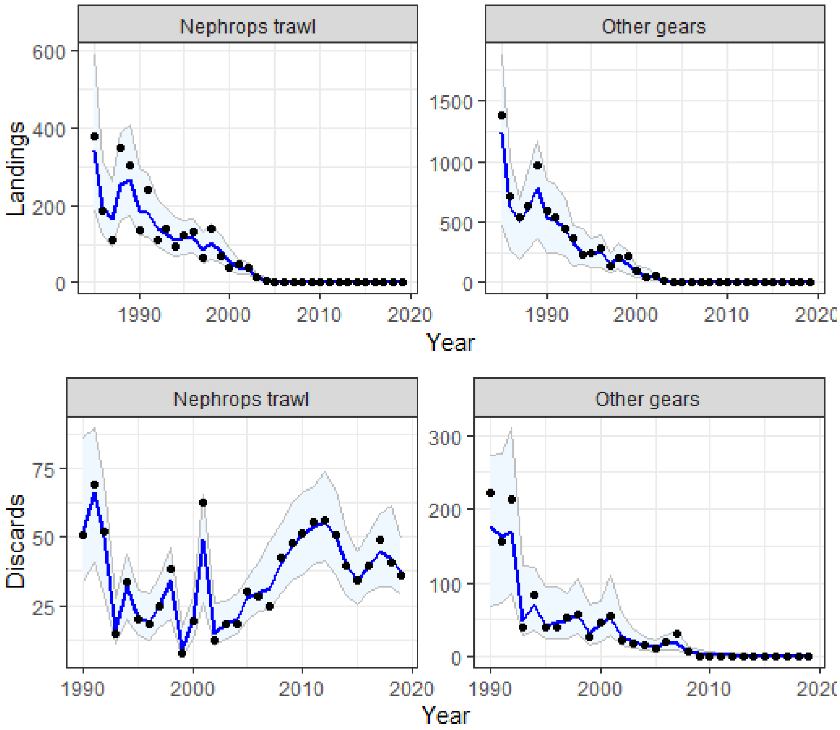


Figure D2. SPM Model fit to the landings and discard data. Solid line shows the median value and the shaded area the 95% credible intervals. Dots show the observations.

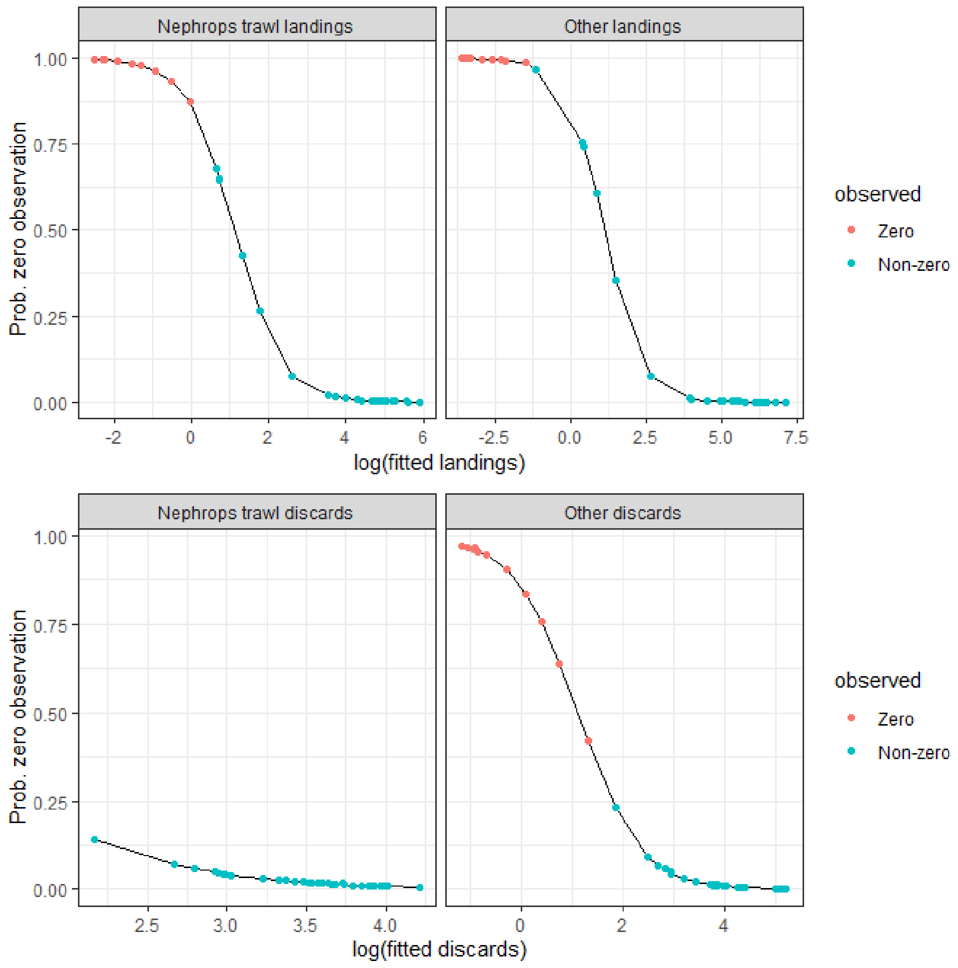


Figure D3.SPM model. The probability of observing a zero value given the true value of landings or discards. The logistic curve is the same for each fleet and catch category. Dots indicate where the observed zeros (red) or non-zero values (blue) occur given the expected catch. Zero values occur where the predicted probability is high.

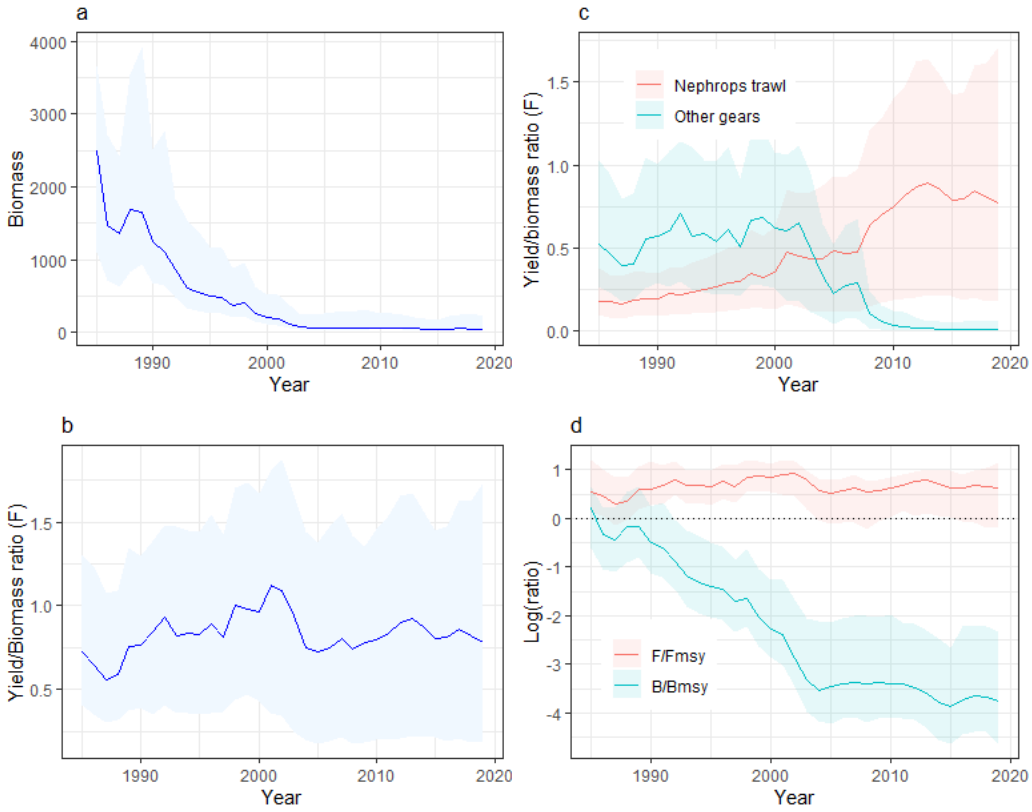


Figure D4. Summary of the Clyde stock assessment from the SPM model. (a) Total biomass (tonnes), (b) Total yield/biomass ratio, F, (c) Yield/biomass ratio by fleet and (d) Stock changes relative to MSY. Dotted line indicates a ratio of 1:1 on a log scale which is the MSY level. Solid line shows the median value and the shaded area the 95% credible intervals.

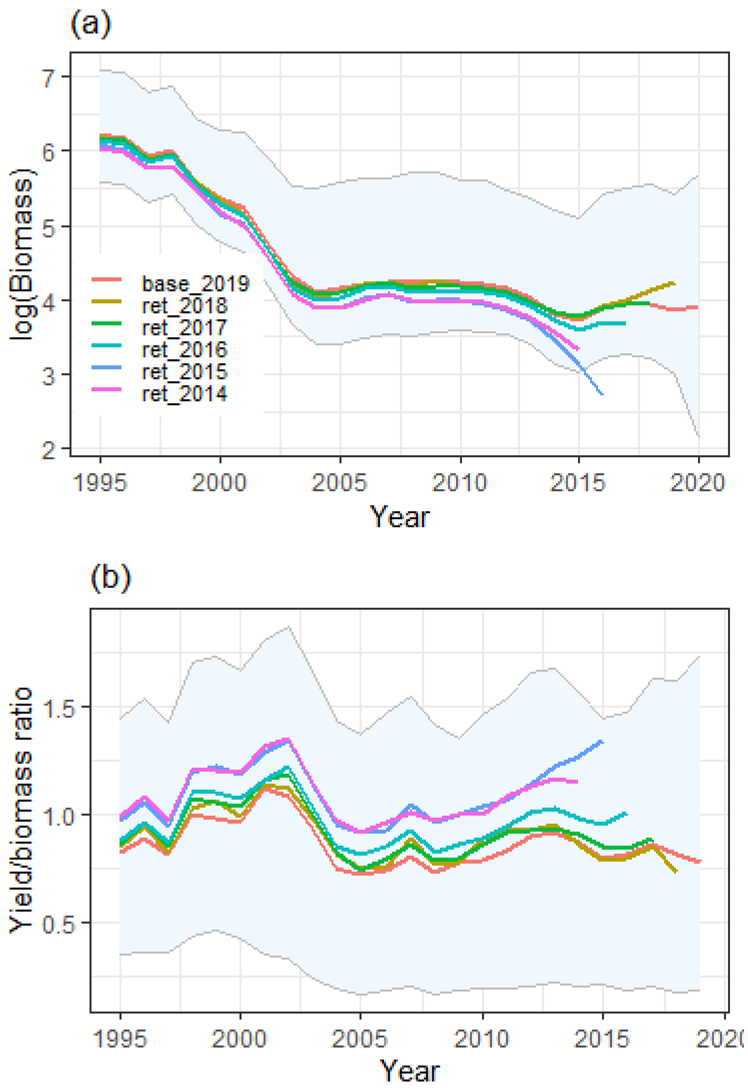


Figure D5. SPM retrospective runs. Lines show median values. Shaded area is the 95% credible interval from the full model (base_2019).

Appendix E: Clyde cod assessment including *Nephrops* creel catches

Introduction

The age structured assessment model (ASM) discussed in the main text and documented in Appendix B uses catches associated with commercial fleets that report landings of cod or are subject to observer coverage where cod catches are recorded. Fishing with creels, while targeting crustaceans, may occasionally catch other species including cod. It has been suggested that cod catches from these static gears may be important. This section considers possible catches of cod in creels directed at *Nephrops* using data from a PhD study (Adey, 2007). Marine Directorate in the Scottish Government indicate they have data on creel bycatch but have not made these data public and consequently were not available for analysis.

Methods

Data reported in the Adey thesis include, for the year 2005 in Loch Fyne, estimates of the number of cod caught per kilogram of *Nephrops* landed (0.111) and the mean weight of individual cod caught (0.33kg). This very limited data nevertheless provides some insight into the likely catches of cod in the Clyde. Here, cod per kilo *Nephrops* landed can be used to estimate cod catchability due to creels and the mean weight gives a strong signal about the selectivity of creels.

A well-established approach to estimating total bycatch from observer programmes is to use a ratio estimator which is scaled to the catch by applying an auxiliary variable to the ratio. In the case of cod bycatch in the *Nephrops* fleet, Adão (2025) used a ratio estimator to calculate cod bycatch with *Nephrops* landings as the auxiliary variable. This gave similar results to fishing effort (number of trips) applied to the mean cod catch per trip. This suggests that *Nephrops* landings can act as a proxy for fishing effort. It will be adequate provided the *Nephrops* biomass shows no long-term time trend during the time period in question. Here we assume that *Nephrops* landings, *L*, from the creel fleet is a proxy for fishing effort. We can then write fishing mortality due to creels as:

$$F_{a,y,creel} = q_{creel} L_{y,creel} s_{a,creel}$$

Where *q* represents catchability, *s* is selectivity and *a* and *y* refer to age and year respectively. The catch of cod by creels is then:

$$c_{a,y,creel} = F_{a,y,creel} N_{a,y} \left(1 - \exp\left(-Z_{a,y}\right)\right) / Z_{a,y}$$

The total catch of cod per unit weight *Nephrops, R,* is then :

$$R_{y,creel} = \frac{\sum_a c_{a,y,creel}}{L_{y,creel}}$$

And the mean weight of an individual cod caught in creels is:

$$\bar{W}_{y,creel} = \frac{\sum_a c_{a,y,creel}\, w_{a,y,creel}}{\sum_a c_{a,y,creel}}$$

The observed values of *R* and *W* can now be included in the likelihood to allow the estimation of *q* and *s* for creels, where:

$$R'_{2005,creel} \sim lognormal(\log(R_{2005,creel}), sd)$$

$$\bar{W}'_{2005,creel} \sim lognormal(\log(\bar{W}_{2005,creel}), sd)$$

Since there is only one observed value for each datum, the standard deviation, *sd*, cannot be estimated within the model. We set this value to 0.2. We also assumed that selectivity of creels can be described by a two parameter gamma curve as is used in the main model (Appendix B, equation T1.5).

Values of *Nephrops* landings from creels were available from 1985-2019. A run using these data and the nominal values from Adey's thesis gave a reference assessment comparable to the main model base run and is labelled "creel". Three further runs were carried out as sensitivity tests around the Adey values. Since it is suggested that lobster/crab creels may have higher catchability and take larger fish these runs were configured to reflect this (Table E1).

Table E3. Values used for creel data in sensitivity runs.

Run acronym	Number of cod per unit effort (2005)	Cod mean weight (kg)	Creel fishery assumption
creel	0.111	0.33	*Nephrops* creel fishery only
creel_highq	0.500	0.33	Expanded creel fishery
creel_highsel	0.111	0.60	Creel fishery catching larger cod
creel_highselq	0.500	0.60	Expanded creel fishery catching larger cod

Here the *creel_highq* run considers approximately five times the catchability of *Nephrops* creels which is equivalent to increasing effort/catchability. Run *creel_highsel* assumes approximately double the mean weight of cod caught in *Nephrops* creels. These are extreme values intended to test the robustness of the model.

Results

Figure E1(a) shows the trend in SSB for the sensitivity runs. All show a similar long term decline with the estimated median values lying within the credible interval of the base run except for a few years for the most extreme assumptions about catchability and selectivity.

Figure E1(b) shows the estimates of mean fishing mortality in the assessment. Here too, the trends in all runs are very similar apart from the most recent years where there is a spread of estimates. However, all the values are large ranging from 1.25 in the base run to 2.00 in the most extreme creel fishery. As with SSB, all estimates are within, or very close to, the base run credible intervals.

The fishing mortality year effect by fleet (f_y; see equation T1.3 in Appendix B)) and associated creel selectivity are shown in Figure E2 for each sensitivity run. As expected, as the size of the creel fishery is increased, the associated value of f_y increases. However, the f_y estimates for the remaining fleets do not change by a comparable magnitude and remain high for the *Nephrops* trawl fleet. In the latter case the value of f_y decreases from ~1.6 to ~0.9, while the creel f_y increases from ~0.4 to ~2.4. Even when the creel fishery is scaled up by a factor of 5, the f_y value for *Nephrops* trawl only decreases from ~1.6 to ~1.4. The estimates of fishing mortality for the *Nephrops* trawl fleet do not appear to be sensitive to the assumption about the creel fishery.

Figure E3 shows the estimated catch by creels compared to the observed values for the *Nephrops* trawl fleet. Creel catches from 1990 onwards are low apart from those estimated from the most extreme fishery ("creel_highselq"). Here recent catches exceed the trawl fishery estimates but are implausibly large. Using simply the direct observations from the *Nephrops* creel fishery ("creel"), the estimated catches lie well below the trawl fishery. The expanded fishery scenario ("creel_highq") produces estimates comparable in scale to the trawl fishery. This implies that a very large creel fishery is required to explain catches approaching the trawl fishery bycatch.

Discussion

The very limited data on cod bycatch in creels means that there is considerable uncertainty in any results and the estimates should be seen as illustrative of possible effects of creel catches. Despite the uncertainties, the inclusion of creel data does not reveal any major change to the perception of the scale of total fishing mortality or SSB. Fishing mortality due to *Nephrops* creels appears to be considerably lower than other gears and makes a minor contribution to total mortality. Sensitivity runs, where observed values for *Nephrops* creels are disturbed by a large amount to simulate a more substantial creel fishery, do not change the perception that *Nephrops* trawls generate a high fishing mortality on cod. In important reason for this is that creels select the smallest fish by virtue of their design. These juveniles are subject to exploitation by creels before reaching the size of maximum selection by trawls. As a result, when including creel catches, the model inflates the estimates of recruiting fish but also estimates a high juvenile fishing mortality with a small net effect on the estimates of SSB and mean F.

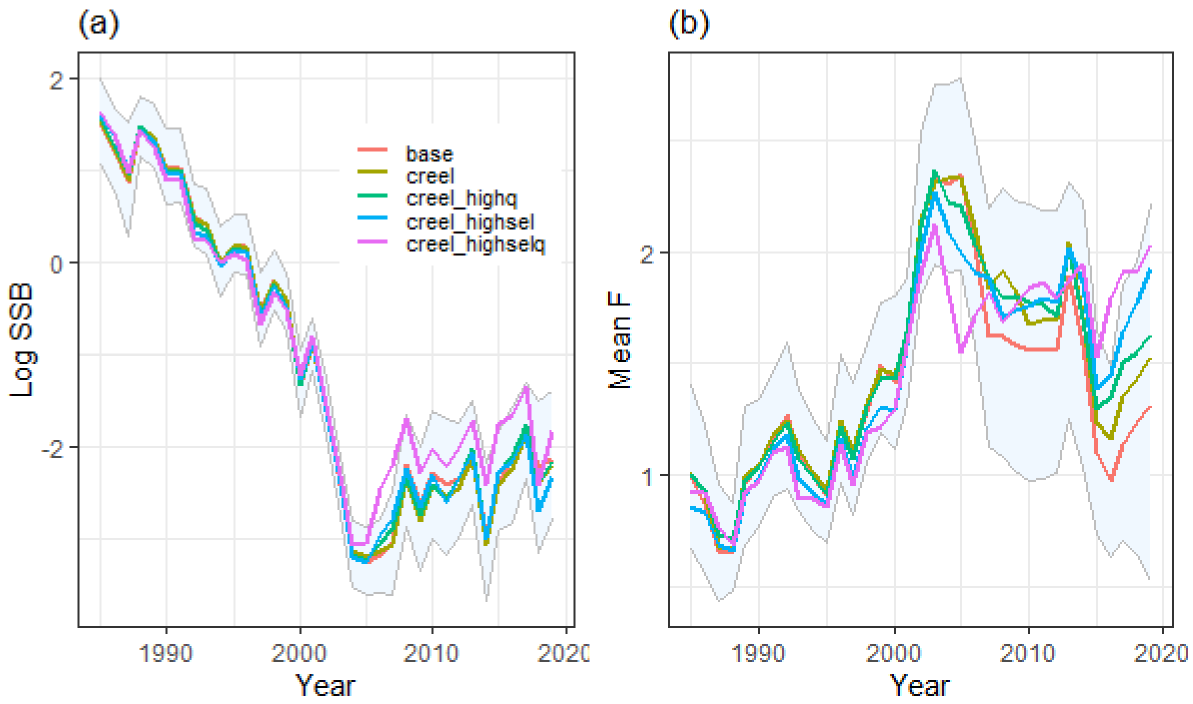


Figure E6. Sensitivity results for a range of assumptions about the creel fishery. "base"= run without creel data as described in the main text, "creel"=run with Nephrops creel data, "creel_highq"= run assuming 5 times Nephrops creel catchability, "creel_highsel"= run assuming higher mean weight of cod caught per creel, "creel_high selq"= run assuming both high catchability and higher mean weight of cod caught per creel. Blue shading indicates 95% credible interval for the base run. All sensitivity runs lie within the credible intervals of the base run except in a few years for the "creel_highselq" run.

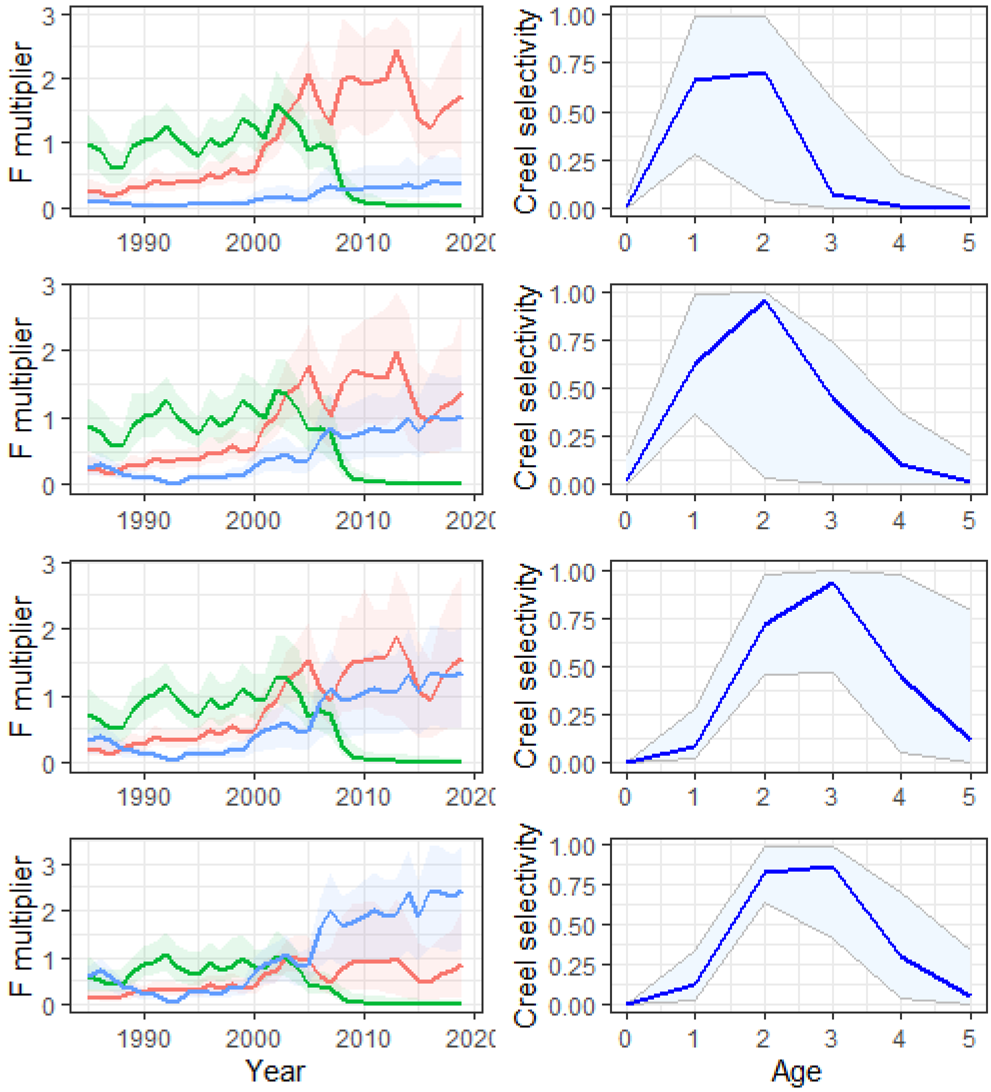


Figure E7. Fishing mortality multiplier for each fleet and the selectivity pattern for the creel fishery under various assumptions about creel catchability and selectivity. Red line= Neprhops trawl fleet, blue line= creel fleet, green line=other gears. Top row=Run with Nephrops creel data, second row=run with high creel catchability (creel_highq), third row=run with high mean weight per creel (creel_highsel), fourth row=run with high catchability and high mean weight per creel (creel_highselq).

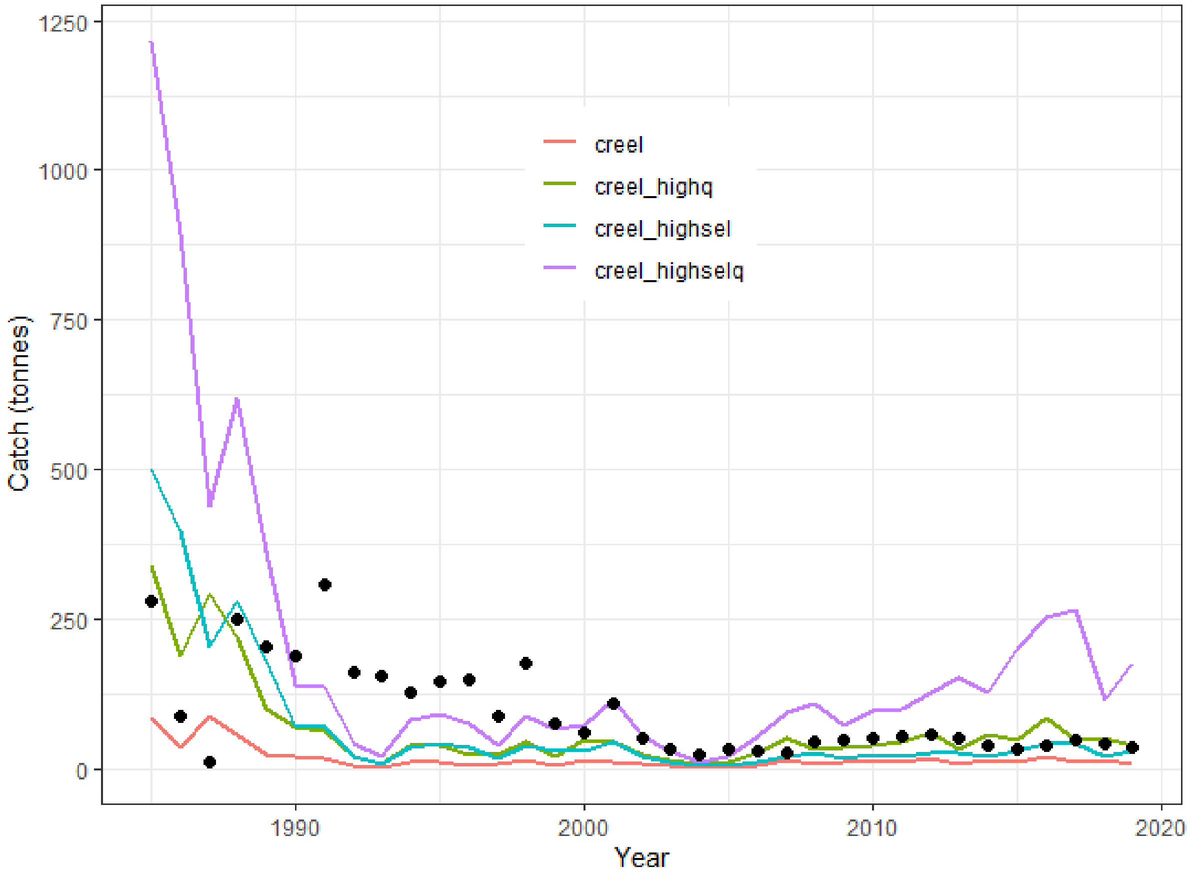


Figure E8. Estimated catches of cod from creels under different assumptions about creel catchability and selectivity. "creel"=run with Nephrops creel data, "creel_highq"= run assuming 5 times Nephrops creel catchability, "creel_highsel"= run assuming higher mean weight of cod caught per creel, "creel_high selq"= run assuming both high catchability and higher mean weight of cod caught per creel. Dots show the estimated catches from Nephrops trawl calculated from the observer programme.

Reference

Adey, Jonathan Max (2007). Aspects of the sustainability of creel fishing for Norway lobster, *Nephrops* norvegicus (L.), on the west coast of Scotland. Unpublished PhD thesis, University of Glasgow, http://theses.gla.ac.uk/524/

Appendix F: Processing of market sampling data for the Clyde

Data description

Market sampling data for ICES Region VIa for the period 1985-2008 were provided by the Marine Directorate. The data consisted of:

Landed weight data, consisting of kg landed per year and quarter, distinguished by species, statistical rectangle and gear type.

Sampled numbers at length data, consisting of numbers measured per year and month, distinguished by species, statistical rectangle and gear type.

Sampled age at length data, consisting of age and length of individual fish sampled per year and month, distinguished by species, statistical rectangle and gear type.

Each of these data sets was filtered to select data on cod from statistical rectangles 39E4, 39E5, 40E4 and 40E5 which cover the Firth of Clyde. Rectangles 30E4 and 40E4 included sea surface area outside the Clyde, in the Sound of Jura and North Channel, but there was no basis for applying any adjustments to exclude possible landings or sampling of catches in these external areas.

Landed weight data

Data on total weights landed covered the period 1985 – 2008. Three gears (Light Trawl, Nephrops Trawl, and Seine) accounted for more than 90% of the quarterly averaged landings (Table F1). The two outer-area statistical rectangles (39E4 and 40E4) accounted for almost 90% of landed weight (Table F2).

Table F1. Quarterly averaged landed weights (1985-2008) by gear type.

Gear Name	Quarterly average landed kg	Proportion of total
Light Trawl (under 90ft)	62118.1	0.5691
Nephrops Trawl	28435.4	0.2605
Seine	13761.4	0.1261
Others	3674.8	0.0337
Two Boat - Demersal (Pair Trawl)	510.1	0.0047
Trawl	430.9	0.0039
Queen Trawl	152.6	0.0014
Two Boat Pelagic - (Industrial)	36.2	0.0003
Creel Fishing	11.0	0.0001
Scallop Dredging	9.1	0.0001
Single Boat - Pelagic	6.1	0.0001
Two Boat Pelagic - (Herring)	0.3	0.0000
Total	**109146.0**	**1**

Table F2. Quarterly averaged landed weights (1985-2008) by Statistical Rectangle.

Stat.Rectangle	Quarterly average landed kg	Proportion of total
39E4	61530.9	0.5637
40E4	36362.3	0.3332
40E5	7798.9	0.0715
39E5	3454.0	0.0316
Total	**109146.0**	**1**

Numbers at length data

Sampled length distributions covered the period 1987 – 2007, and were gathered from 1937 vessel trips (mean number of trips per quarter = 23) by Nephrops Trawlers (93.4%), Seines (2.7%) and Light Trawlers (3.9%). The majority of sampled trips were from rectangle 39E5 (60.5%), and the fewest from 39E5 (6.5%) (Table F3). Hence, compared to the distribution of landed weights, the market sampling under-sampled Seine and Light Trawl trips, and trips from statistical rectangle 40E4.

Table F3. Mean number of vessel trips sampled for length distributions per quarter (1987-2007), per gear type and statistical rectangle.

Stat.Rectangle	**Nephrop Trawl**	**Seine**	**Light Trawl**	**Total**	**Proportion**
39E4	12.94	0.40	0.60	**13.94**	**0.6045**
40E4	2.90	0.01	0.10	**3.01**	**0.1306**
40E5	4.40	0.01	0.19	**4.61**	**0.1998**
39E5	1.29	0.20	0.01	**1.50**	**0.0650**
Total	**21.54**	**0.63**	**0.89**	**23.06**	**1**
Proportion	**0.9339**	**0.0274**	**0.0387**	**1**	

Age-length data

Age data were available for the period 1987 – 2004. As for the sampled length distributions, Nephrops Trawlers were most intensively sampled, and Seiners least. Rectangle 39E4 was most intensively sampled, and 39E5 the least (Table F4). Sampled individuals ranged from 25 cm to 101 cm length, and ages 1 to 9. As for length distributions, Light Trawler and Seine were under-sampled for age determination relative to the landed weights, but aged individuals were more evenly distributed across statistical rectangles.

Table F4. Mean number of individual fish sampled for age determination per quarter (1987-2004), per gear type and statistical rectangle.

Stat.Rectangle	**Nephrop Trawl**	**Seine**	**Light Trawl**	**Total**	**Proportion**
39E4	157.28	20.28	23.24	**200.79**	**0.4174**
40E4	86.93	0.79	8.42	**96.14**	**0.1998**
40E5	117.28	1.53	10.96	**129.76**	**0.2697**
39E5	46.89	6.79	0.69	**54.38**	**0.1130**
Total	**408.38**	**29.39**	**43.31**	**481.07**	**1**
Proportion	**0.8489**	**0.0611**	**0.0900**	**1**	

Data analysis

The total landed weight from all four statistical rectangles and all gears combined (Figure F1) showed a strong annual cycle, with peak landings in quarter 1 coinciding with a fishery on spawning cod concentrated in rectangle 39E4 until its closure in 2001.

This annual cycle, combined with the rapid growth rate of cod made it necessary to conduct the numbers-at-age computation at quarterly intervals rather than aggregating the sampling data to annual intervals.

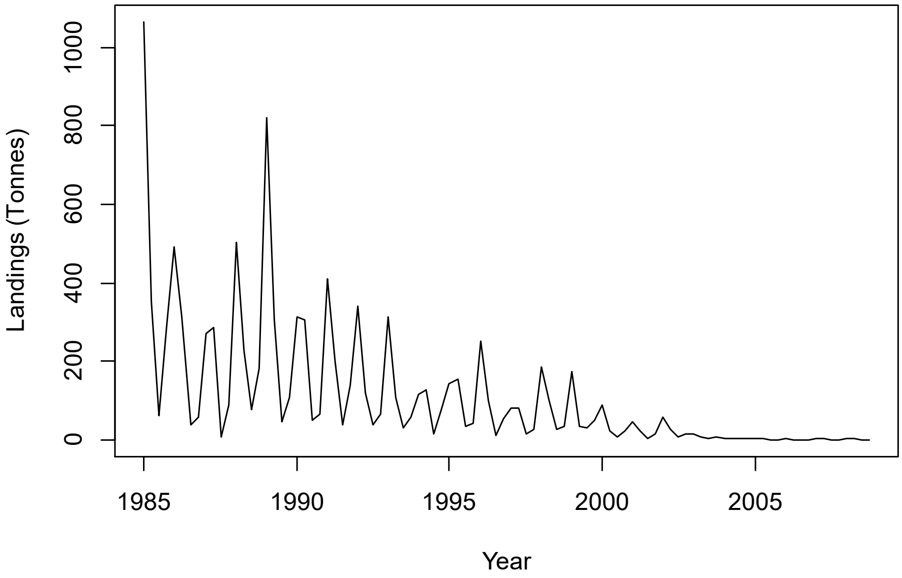


Figure F1. Cod landings over successive quarterly intervals, 1985-2008, from all four statistical rectangles covering the Clyde, by all gears combined.

2.1 Raising the sampled length distributions to totals for the Clyde

Parameters for quarterly weight-length relationships were assembled by averaging of the monthly parameters provide in Coull et al 1989. The equations for weight given length are:

$$Gutted\ weight = a_q . L^b$$

$$Live\ weight = c . Gutted\ weight$$

From Coull et al 1989, the parameters *b* and *c* are independent of sampling month (2.8571 and 1.17 respectively). Quarterly averaged values of a_q were 0.0171, 0.0170, 0.0178 and 0.0180 for quarters 1 to 4 respectively, assuming weight in grammes.

The quarterly total weight of the individuals measured for length on the fish market was then

$$W_{sampled} = \sum_{k=length_{min}}^{k=length_{max}} N_{length_{k\,sampled}} . c . a . {length_k}^b$$

Here, N_{length_k} denotes the number of measured fish in length class *k* in a given quarter.

The total quarterly numbers at length of fish caught by the fleet was then

$$\mathrm{N}_{{length_k}_{landed}} = N_{{length_k}_{\cdot sampled}} . \frac{W_{landed}}{W_{sampled}}$$

Although Nephrops Trawlers accounted for only 26% of cod landed weight over the monitoring period (Table F1), the market sampling programme was strongly biassed towards these vessels (93% of trips sampled (Table F3). Hence, there were many instances where the quarterly landings by Light Trawlers and Seine Netters (69.5% of landings) were unsampled ($W_{sampled}$ = 0).

We proposed to substitute sampled numbers-at-length data from Nephrops Trawlers where Light Trawlers and Seine Netters Trawls (hereafter referred to as “Other Gears”) were unsampled. To check the viability of this substitution we compared the whole-Clyde sampled length distributions for Nephrops Trawlers and Other Gears in years/quarters where both existed (Figure F2). Although no formal statistical test was performed there was no evidence of systematic differences in the sampled length distributions.

The designated substitutions of sampled length distributions are shown in Tables F5 and F6.

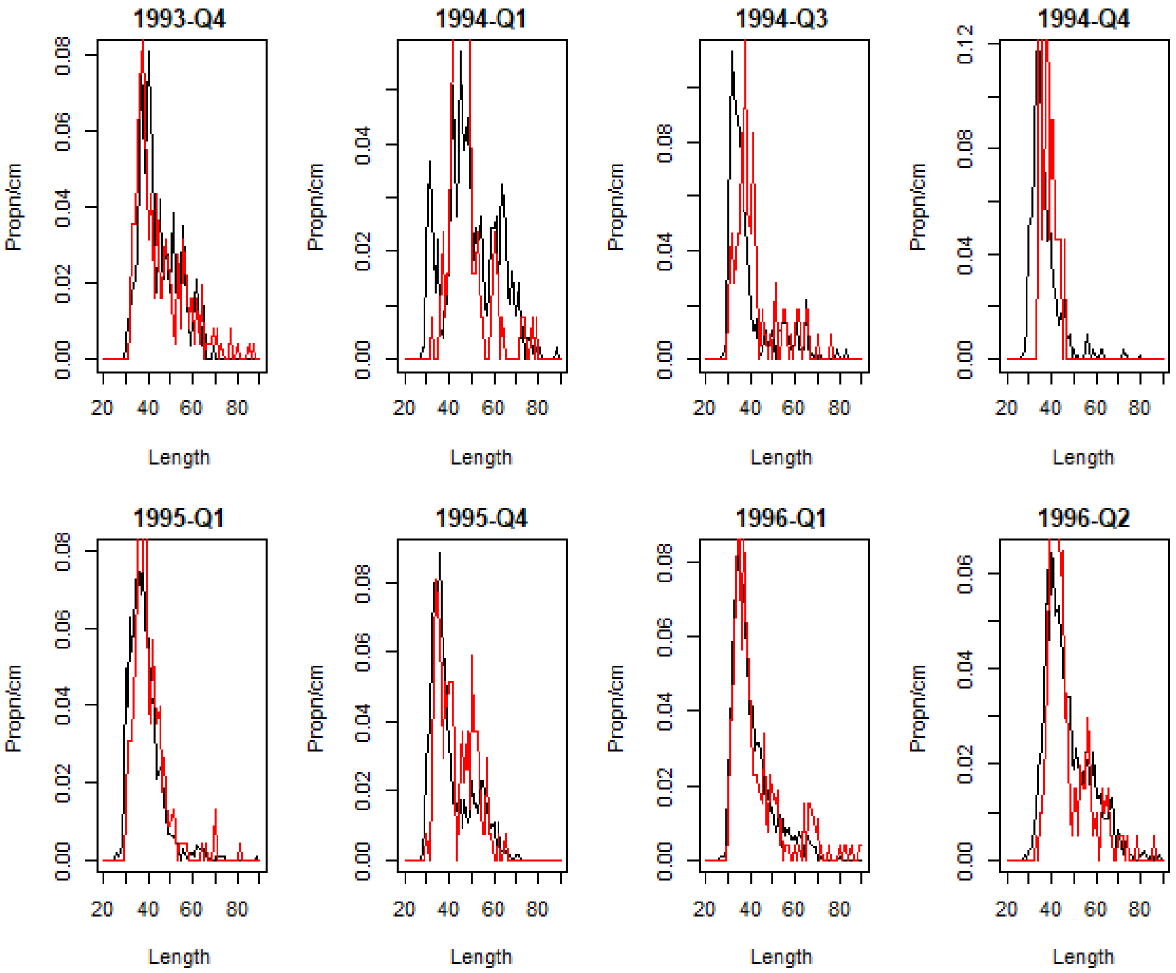


Figure F2. Examples of sampled length distributions from Nephrops trawl landings (black) and “Other gears” (Light trawl and Seine) landings (red) in years and quarters where data from both groups exist.

Table F5. Quarterly weight of cod landing by Nephrops Trawlers which were sampled for length measurements (kg), total weights landed by the fleet (kg), and the designation of sampling data used to estimate numbers-at-length for the whole fleet (NT=Nephrops Trawl sample data; OG=Other Gear sample data (Light Trawl and Seine))

Year/Quarter (yyyyqq)	**Sampled weight landed (kg)**	**Total weight landed (kg)**	**Designated source of data as the basis for estimating total numbers-at-length landed**
198501	0	158415	None available
198502	0	58874	None available
198503	0	36660	None available
198504	0	126599	None available
198601	0	82560	None available

198602	0	48932	None available
198603	0	28455	None available
198604	0	27275	None available
198701	18	28312	NT
198702	349	32232	NT
198703	41	3627	NT
198704	318	45682	NT
198801	783	190086	NT
198802	327	64461	NT
198803	740	33163	NT
198804	688	62455	NT
198901	504	153319	NT
198902	1003	94790	NT
198903	710	22292	NT
198904	763	33124	NT
199001	391	44701	NT
199002	629	45831	NT
199003	357	20021	NT
199004	363	25887	NT
199101	702	125756	NT
199102	855	49042	NT
199103	395	18184	NT
199104	249	46892	NT
199201	953	53336	NT
199202	420	31164	NT
199203	301	12656	NT
199204	561	12770	NT
199301	880	84551	NT
199302	776	31009	NT
199303	361	13239	NT
199304	347	11992	NT
199401	815	27844	NT
199402	795	38246	NT
199403	250	10018	NT
199404	386	19036	NT
199501	783	57282	NT
199502	1471	49291	NT
199503	831	10395	NT
199504	720	8077	NT
199601	839	72390	NT
199602	1575	42227	NT
199603	666	6419	NT
199604	549	8620	NT
199701	724	24262	NT
199702	872	23283	NT
199703	210	3504	NT

199704	415	12183	NT
199801	1512	75698	NT
199802	618	37143	NT
199803	133	12899	NT
199804	261	12586	NT
199901	699	47936	NT
199902	316	13373	NT
199903	141	3081	NT
199904	67	2835	NT
200001	178	17262	NT
200002	192	6063	NT
200003	99	2839	NT
200004	178	15389	NT
200101	646	27023	NT
200102	212	15634	NT
200103	236	1465	NT
200104	132	1893	NT
200201	523	20543	NT
200202	373	13146	NT
200203	132	2273	NT
200204	176	2085	NT
200301	572	7987	NT
200302	222	2965	NT
200303	83	932	NT
200304	141	1528	NT
200401	339	2438	NT
200402	257	1071	NT
200403	32	197	NT
200404	85	1280	NT
200501	257	2643	NT
200502	50	744	NT
200503	27	95	NT
200504	65	25	NT
200601	122	1360	NT
200602	99	246	NT
200603	5	12	NT
200604	20	36	NT
200701	129	1122	NT
200702	87	711	NT
200703	23	1	NT
200704	0	0	None available
200801	0	976	None available
200802	0	636	None available
200803	0	191	None available
200804	0	18	None available

Table F6. Quarterly weight of cod landing by Light Trawlers and Seiners which were sampled for length measurements (kg), total weights landed by all Other Gears (predominantly Light Trawls and Seines) (kg), and the designation of sampling data used to estimate numbers-at-length for the whole "Other Gears" fleet (NT=Nephrops Trawl sample data; OG=Other Gear sample data (Light Trawl and Seine))

Year/Quarter (yyyyqq)	Sampled weight landed (kg)	Total weight landed (kg)	Designated source of data as the basis for estimating total numbers-at-length landed
198501	0	906506	None available
198502	0	292511	None available
198503	0	25581	None available
198504	0	157752	None available
198601	0	409947	None available
198602	0	263553	None available
198603	0	10719	None available
198604	0	28548	None available
198701	0	241306	NT
198702	72	252163	OG
198703	89	2747	OG
198704	154	43697	OG
198801	197	312898	OG
198802	142	163353	OG
198803	62	43426	OG
198804	61	118922	OG
198901	552	668606	OG
198902	80	211669	OG
198903	77	21529	OG
198904	218	72243	OG
199001	1068	267495	OG
199002	246	259790	OG
199003	102	28002	OG
199004	255	36871	OG
199101	634	284750	OG
199102	280	151856	OG
199103	145	17572	OG
199104	359	90490	OG
199201	865	284845	OG
199202	263	86529	OG
199203	160	24530	OG
199204	163	51993	OG
199301	0	226980	NT
199302	0	77303	NT
199303	15	15084	OG
199304	343	46246	OG

199401	192	87569	OG
199402	85	86938	OG
199403	118	2912	OG
199404	17	56146	OG
199501	207	85706	OG
199502	48	103069	OG
199503	35	23480	OG
199504	146	33437	OG
199601	301	180217	OG
199602	259	55836	OG
199603	0	4407	NT
199604	0	44490	NT
199701	779	54167	OG
199702	0	56537	NT
199703	18	8797	OG
199704	63	14881	OG
199801	0	110855	NT
199802	0	63692	NT
199803	0	11834	NT
199804	0	21300	NT
199901	372	125754	OG
199902	0	20676	NT
199903	0	26566	NT
199904	0	45725	NT
200001	0	72029	NT
200002	0	14795	NT
200003	0	3440	NT
200004	0	8297	NT
200101	0	19094	NT
200102	48	6889	OG
200103	0	2480	NT
200104	0	11751	NT
200201	0	35278	NT
200202	0	13334	NT
200203	0	2859	NT
200204	0	12473	NT
200301	0	4462	NT
200302	0	3389	NT
200303	0	2168	NT
200304	0	3479	NT
200401	0	1676	NT
200402	0	636	NT
200403	0	921	NT
200404	0	795	NT
200501	0	334	NT
200502	0	320	NT

200503	0	287	NT
200504	0	230	NT
200601	0	1083	NT
200602	0	75	NT
200603	0	27	NT
200604	0	0	None available
200701	0	565	NT
200702	0	1754	NT
200703	0	40	NT
200704	0	0	None available
200801	0	45	None available
200802	0	200	None available
200803	0	10	None available
200804	0	0	None available

2.2 Probability of age given length and estimation of numbers landed at age and length.

In general, where a gear type was sampled for numbers-at-length in a given year/quarter, otoliths were also collected or age/length determination. Exceptions were the years 2005-2007, were no individual age data were available. For these years, we substituted the age/length data from corresponding quarters of 2004.

For each year/quarter/gear type, the number of sampled individuals were enumerated in a matrix of age/length classes (annual ages, 1cm length classes; $n(age, length)$). The probability of age given length was then estimated as:

$$P(age, length) = \frac{n(age \mid length)}{\sum_{age_{min}}^{age_{max}} n(length)}$$

Total numbers landed at age and length for each quarter and gear type were then given by :

$$N(age, length) = N(length)\,.\,P(age \mid length)$$

Here, the $N(length)$ refers to the raised numbers at length in the quarterly landings by each gear group. during a given time interval (see section 2.1).

The total numbers landed in each age class for a year/quarter/gear group was then the sum over length classes

$$N(age) = \sum_{length_{min}}^{length_{max}} N(age, length)$$

Annual numbers landed at age for each gear group were derived by summing over respective quarters (Tables F7 and F8).

Table F7. Estimated annual numbers-at-age of cod landed by Nephrops Trawlers (NA indicates no estimate available).

Year	Age0	Age1	Age2	Age3	Age4	Age5	Age6	Age7	Age8
1985	NA	NA	NA	NA	NA	NA	NA	NA	NA
1986	NA	NA	NA	NA	NA	NA	NA	NA	NA
1987	0	124598	16871	5959	3678	185	0	0	0
1988	0	15510	495089	3925	1755	0	0	0	0
1989	0	54671	35162	103851	416	397	1007	94	0
1990	0	60399	66642	2093	6005	114	0	0	0
1991	0	60073	193755	11736	1394	909	179	0	0
1992	0	35395	55778	12610	1021	42	0	56	0
1993	0	10005	111294	6025	1288	232	0	80	40
1994	0	43422	19633	14317	673	165	0	0	0
1995	0	8436	128936	3256	848	171	81	0	0
1996	0	5296	87830	26393	465	144	16	0	0
1997	0	23645	20523	7383	2283	167	27	0	0
1998	0	23637	147630	3054	458	150	0	0	0
1999	0	1539	75296	5099	33	179	0	0	0
2000	0	29475	6090	5079	392	0	0	0	0
2001	0	1791	57152	433	170	42	0	0	0
2002	0	4849	15397	8242	0	39	17	0	0
2003	0	1792	11090	517	258	28	0	0	0
2004	0	1660	2349	600	29	11	0	0	0
2005	0	151	3395	304	14	0	0	0	0
2006	0	40	1307	186	17	0	0	0	0
2007	0	43	1444	382	21	12	0	0	0
2008	NA	NA	NA	NA	NA	NA	NA	NA	NA

Table F8. Estimated annual numbers-at-age of cod landed by “Other Gears” (Light Trawlers and Seine Netters) (NA indicates no estimate available).

Year	Age0	Age1	Age2	Age3	Age4	Age5	Age6	Age7	Age8
1985	NA	NA	NA	NA	NA	NA	NA	NA	NA
1986	NA	NA	NA	NA	NA	NA	NA	NA	NA
1987	0	737249	117392	16855	19942	0	0	0	0
1988	0	98302	712817	13877	1154	1590	0	0	0
1989	0	118396	145215	385928	6462	2423	0	0	0
1990	0	142585	337827	17526	30694	1305	250	0	0
1991	0	95615	321865	47208	898	3134	0	0	0
1992	0	34115	231143	66211	4896	635	306	0	0
1993	0	33950	289817	15878	3809	615	0	199	100
1994	0	75275	77306	22358	2504	912	0	0	456
1995	0	18956	197699	3407	2400	2544	0	0	0
1996	0	19187	158155	52908	4445	2690	81	0	0
1997	0	32227	44131	18842	4585	394	65	0	0
1998	0	35555	222940	4551	632	220	0	0	0
1999	0	13995	74977	36275	3325	403	0	0	0
2000	0	32039	20766	19336	1545	0	0	0	0
2001	0	10213	38474	110	223	30	0	0	0
2002	0	15548	24615	11709	0	67	22	0	0
2003	0	4008	8680	443	248	16	0	0	0
2004	0	1688	1659	493	20	7	0	0	0
2005	0	289	709	111	2	0	0	0	0
2006	0	3	985	124	13	0	0	0	0
2007	0	137	1708	535	21	6	0	0	0
2008	NA	NA	NA	NA	NA	NA	NA	NA	NA